



The Earth's energy balance and the climate system

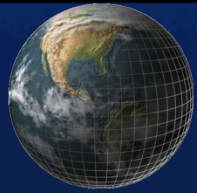


Graeme L Stephens

Director Center for Climate Sciences

JPL, California Institute of Technology

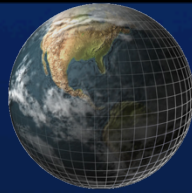
Professor of Earth Observations, University of Reading, UK



Outline

- The Earth's energy (im)balance
- Where is the extra heat going?
- Hemispheric properties
- Meridional transport
 - ERB and the cloud grand challenge
 - Hemispheric symmetry/asymmetry & cross equatorial transport
- Summary

1) One of Today's Main Challenges : Closing the planet's Energy balance



To achieve a balance we make adjustments to our best estimate fluxes – these adjustments are not trivial ($5\text{--}15\text{ Wm}^{-2}$) :

At the TOA in the CERES EBAF data record this is done wrt the observed ocean heat uptake (e.g. Loeb et al., 2012) .

At the surface, two philosophical pathways have been followed

- 1) Small adjustment to turbulent fluxes – Big decrease to radiation - **what is the missing sink of radiant energy?**
- 2) Big increase to turbulent fluxes- Small adjustment to radiation - **where is the missing source of water?**

Box 1 | Updated energy balance

Stephens et al., 2012

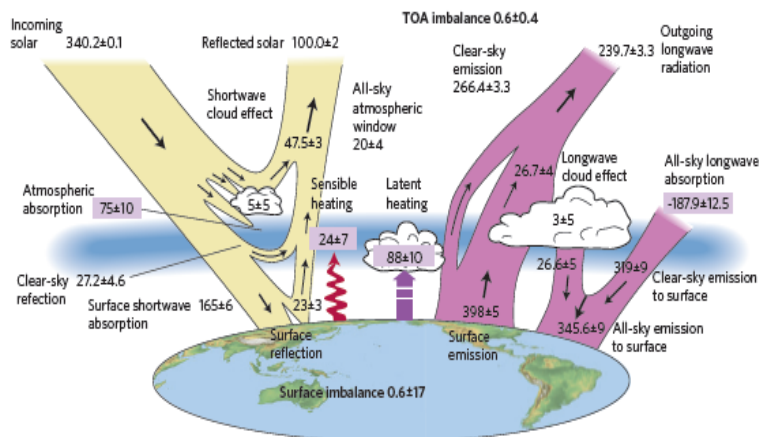
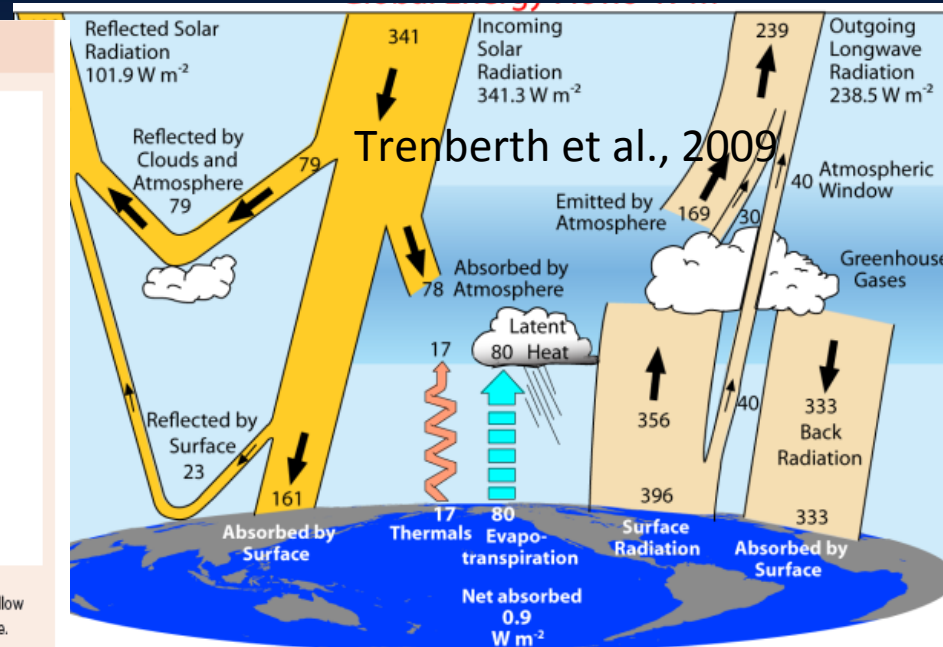
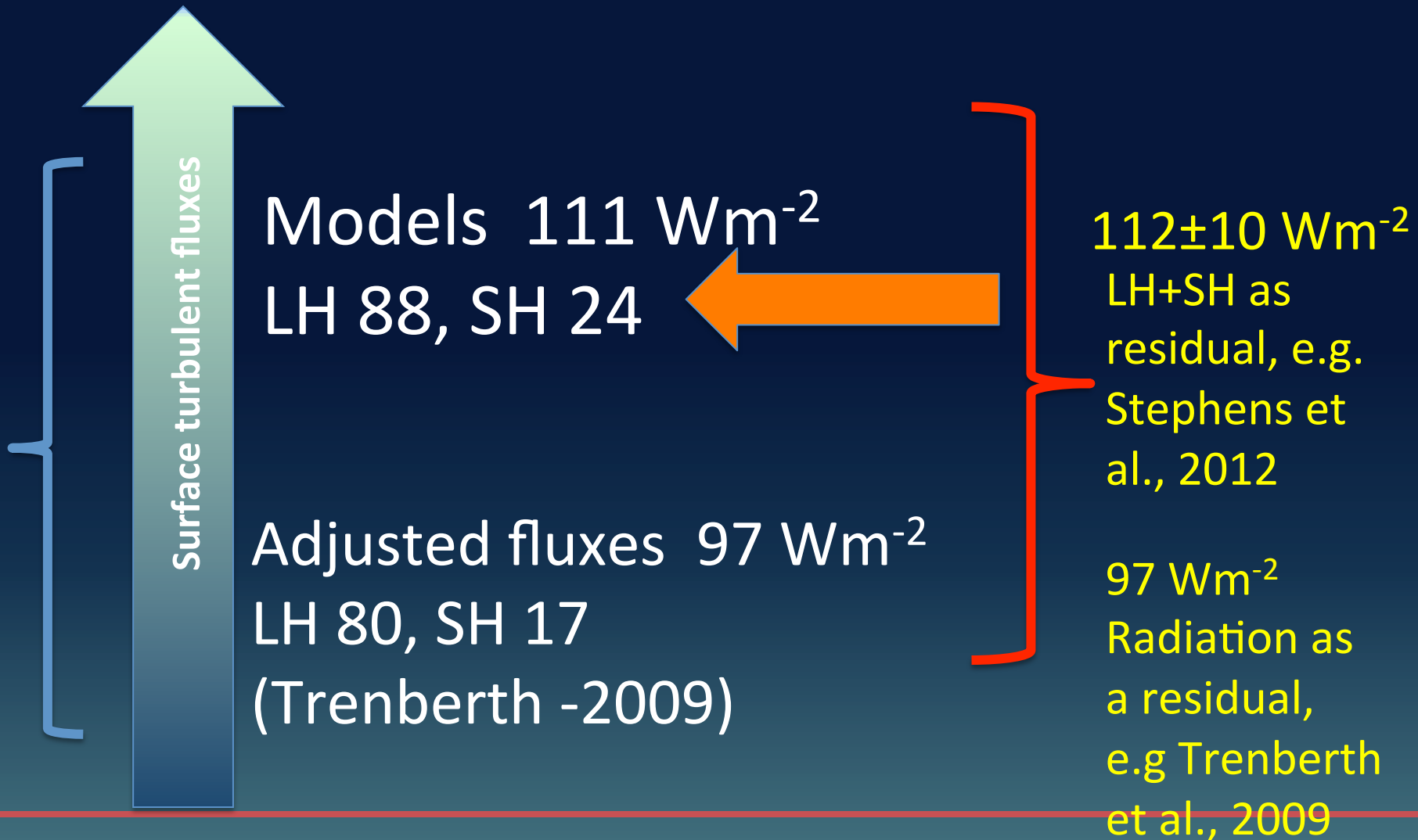
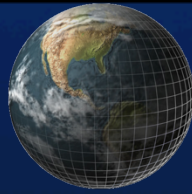


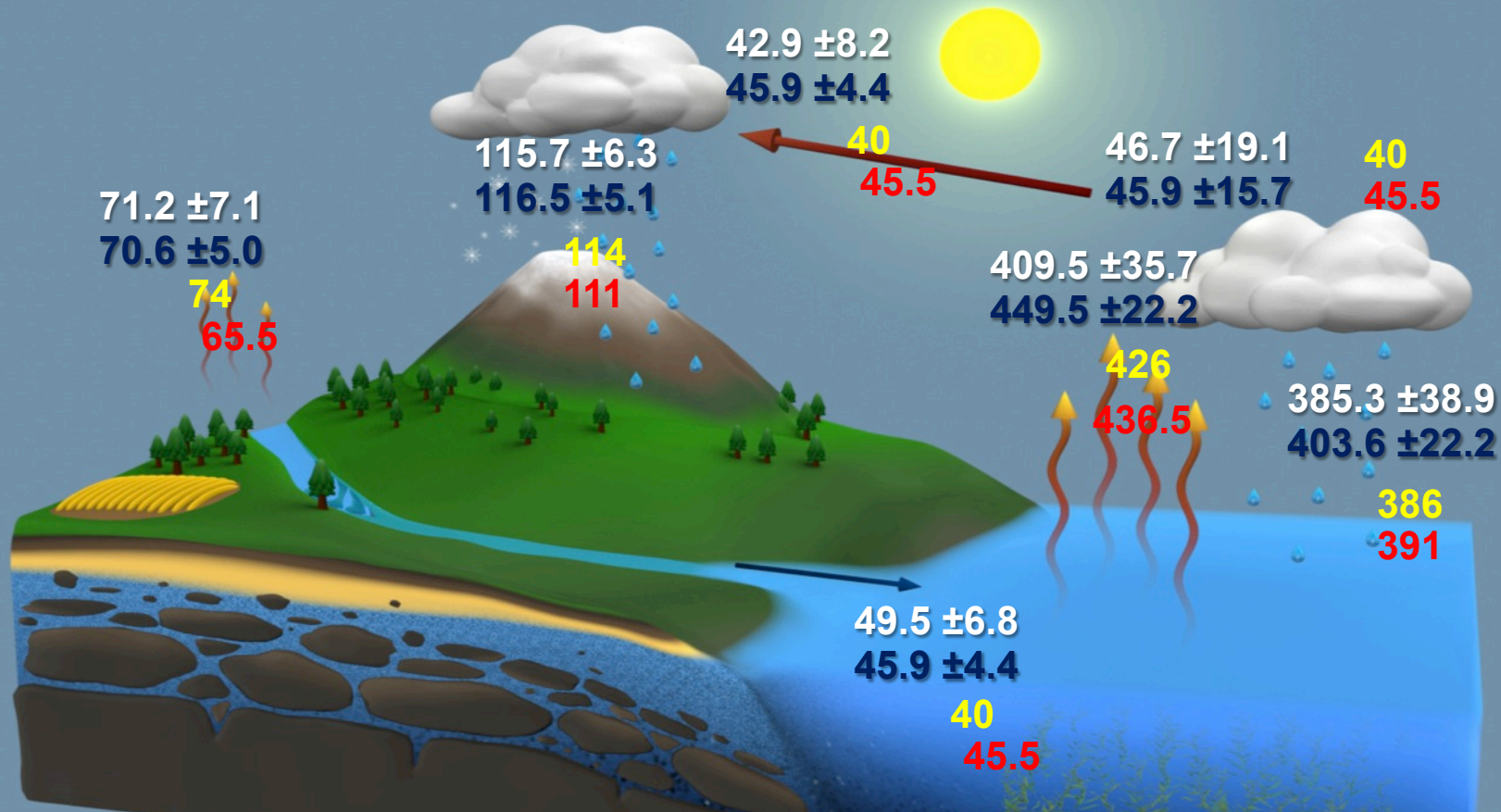
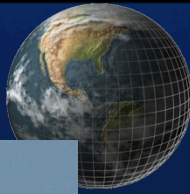
Figure B1 | The global annual mean energy budget of Earth for the approximate period 2000-2010. All fluxes are in Wm^{-2} . Solar fluxes are in yellow and infrared fluxes in pink. The four flux quantities in purple-shaded boxes represent the principal components of the atmospheric energy balance.



The challenge in a nutshell : closing the gap



Global mean water cycle



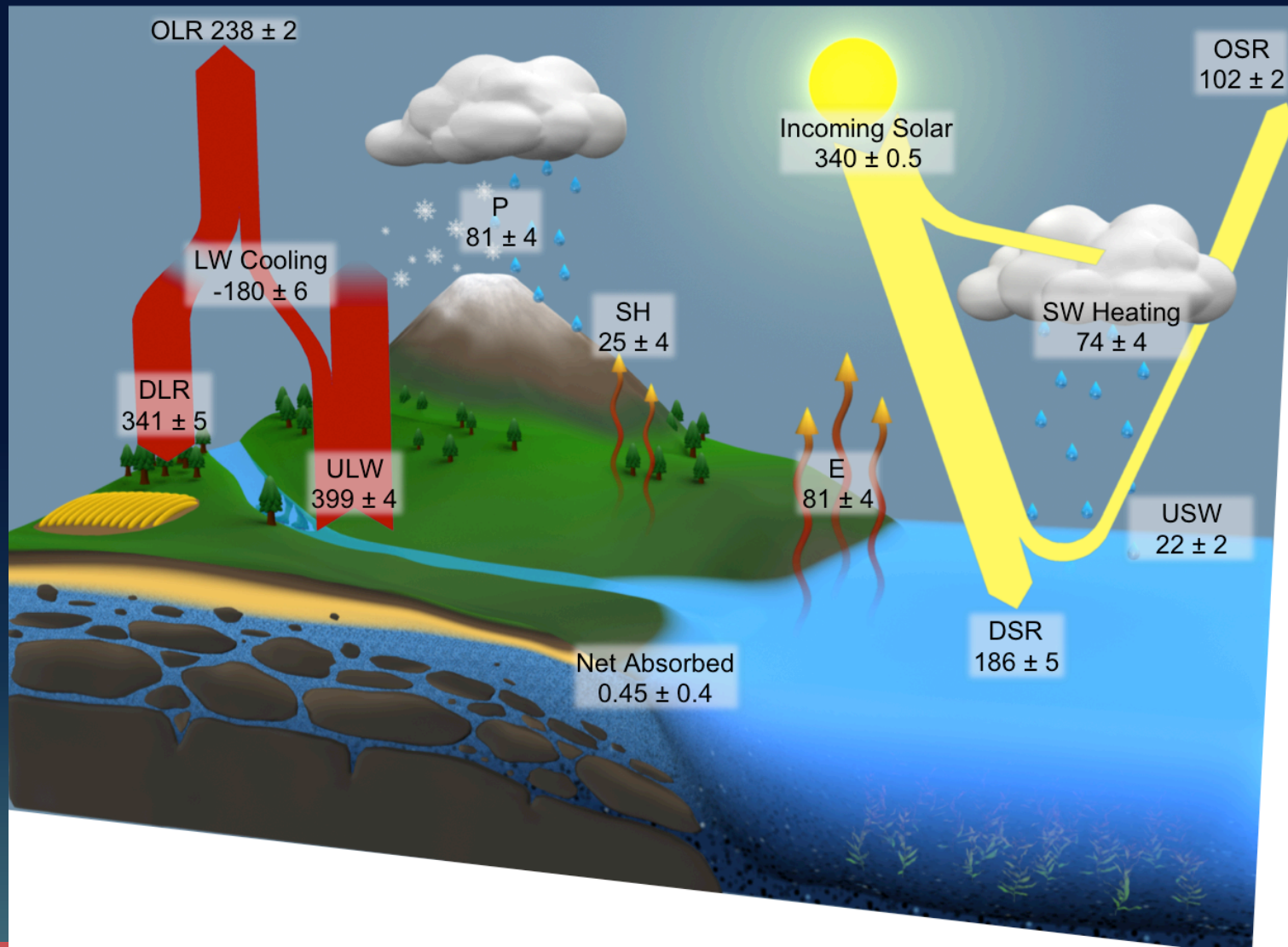
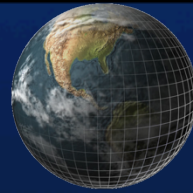
Global mean water fluxes (1,000 km³/yr) at the start of the 21st century
Best guess estimates from observations and data integrating models

When water balance and energy is enforced jointly , uncertainty decreases

Trenberth et al. (2011) for comparison

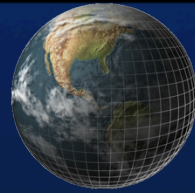
Oki and Kanae (2006, Science) for comparison

'Objective' closure approach

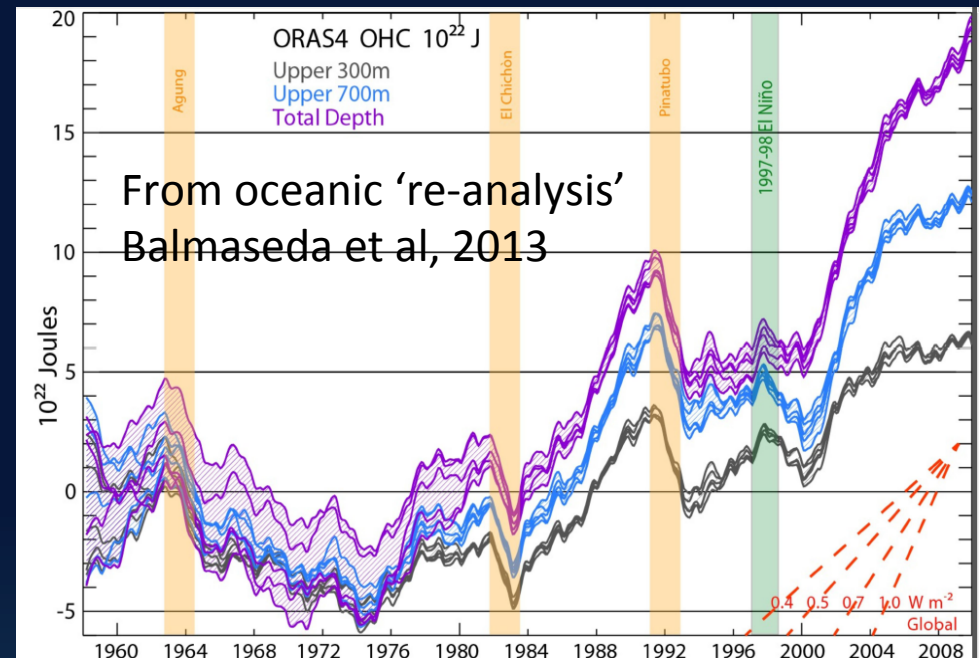
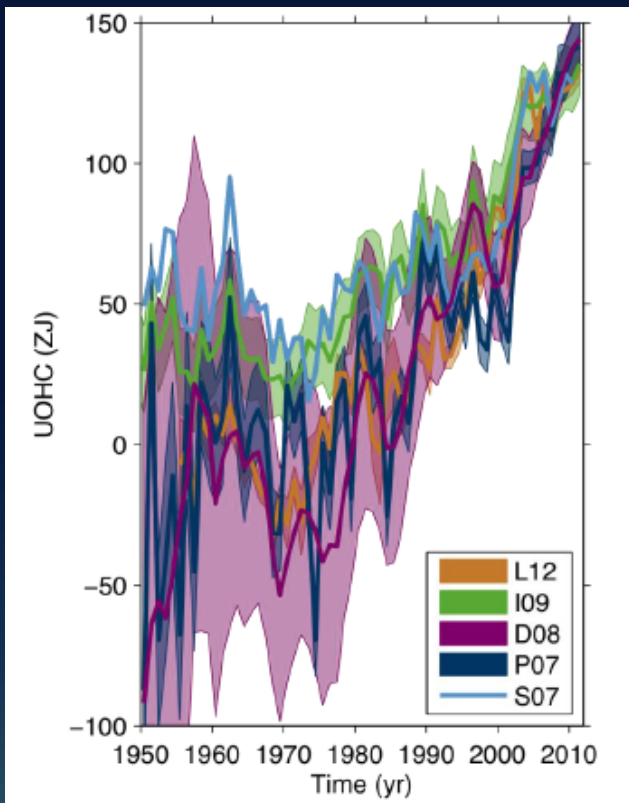


2) The energy imbalance and ocean heat content

Is there major heat draw done below ARGO obs?



From in situ T(z) measurements

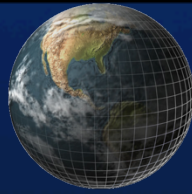


From oceanic 're-analysis'
Balmaseda et al, 2013

What proportion of the change takes place in the deeper ocean?

Why has Earth warmed less over the past decade while oceans appear to have continued to gain heat?

Sea Level Observations



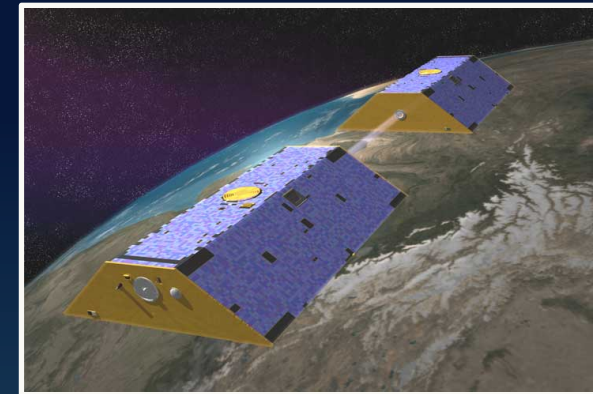
- **Altimetry**: total sea level

$$h_{\text{total}} = h_{\text{mass}} + h_{\text{steric}}$$



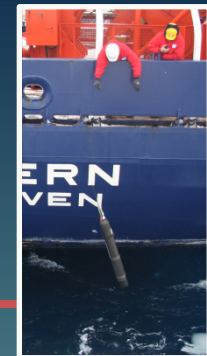
- **GRACE**: mass related changes

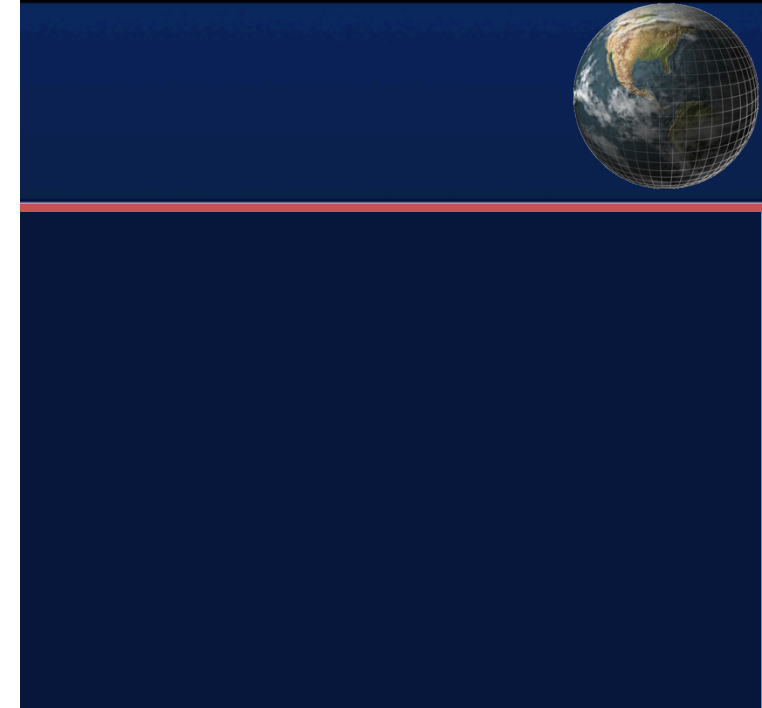
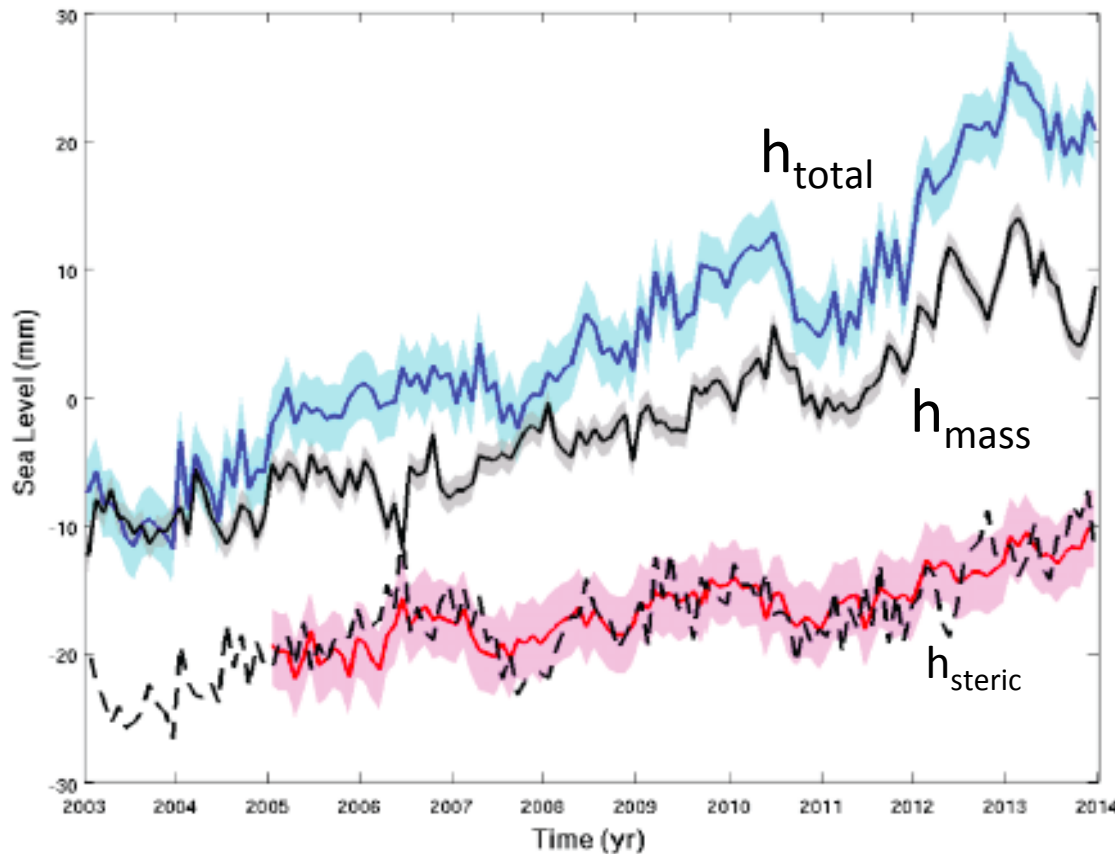
$$h_{\text{total}} = h_{\text{mass}} + h_{\text{steric}}$$



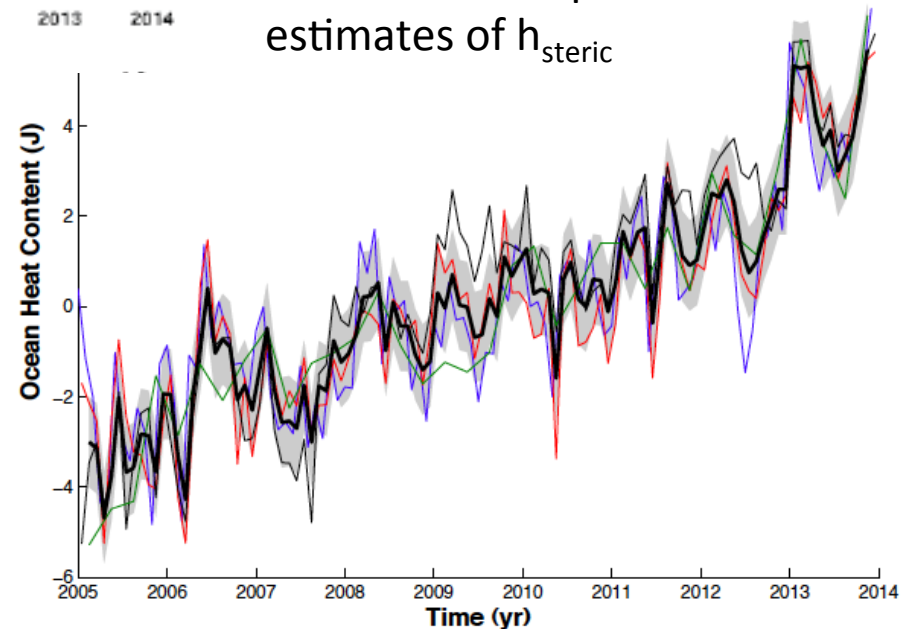
- **ARGO**: steric contributions

$$h_{\text{total}} = h_{\text{mass}} + h_{\text{steric}}$$





OHC from multiple estimates of h_{steric}



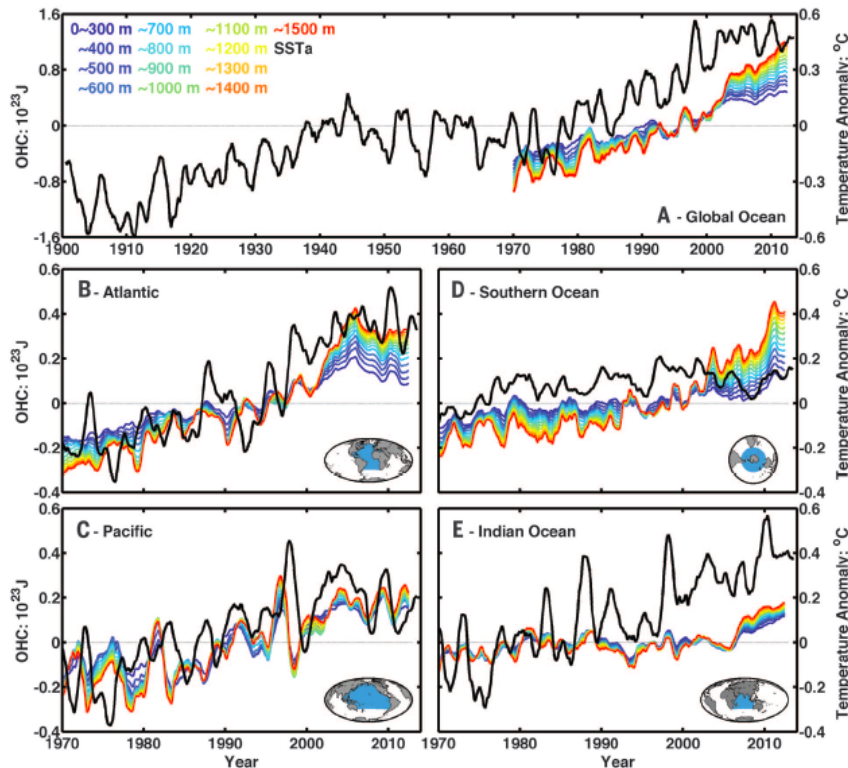
Llovel et al., 2014;

- These results suggest that the heat being added to the ocean over time is occurring between the surface and 2km.
- This heat draw down has continued unabated even though surface temperature rise has paused

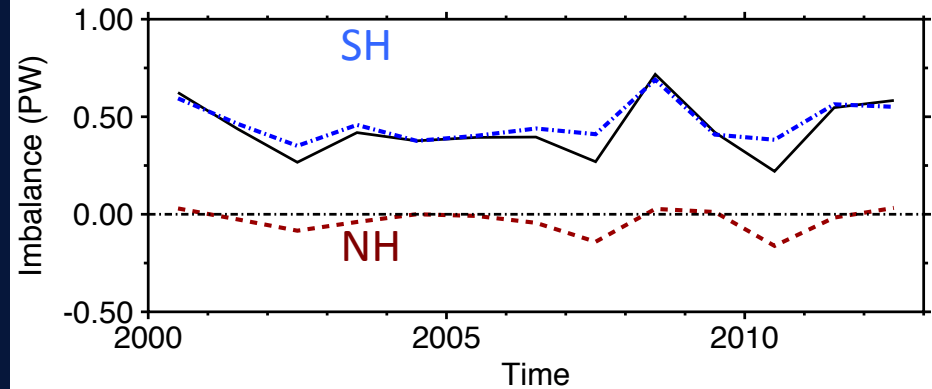
So where in the world's oceans is the heat mostly going?



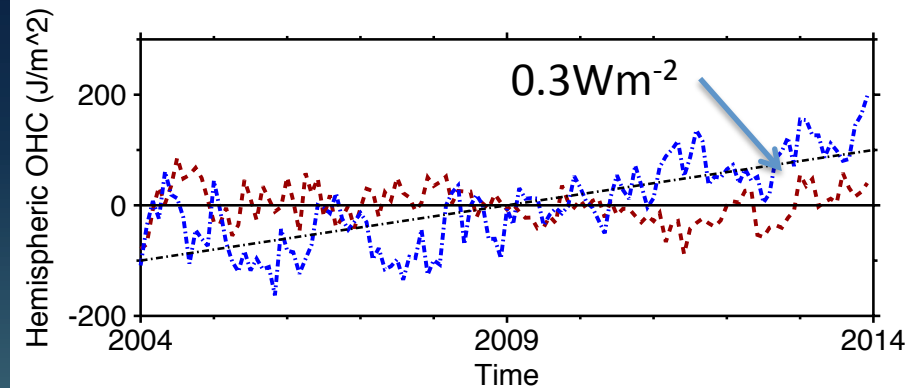
Chen & Tung, 2014



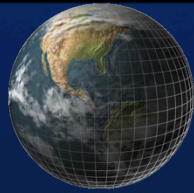
CERES EBAF 2.7



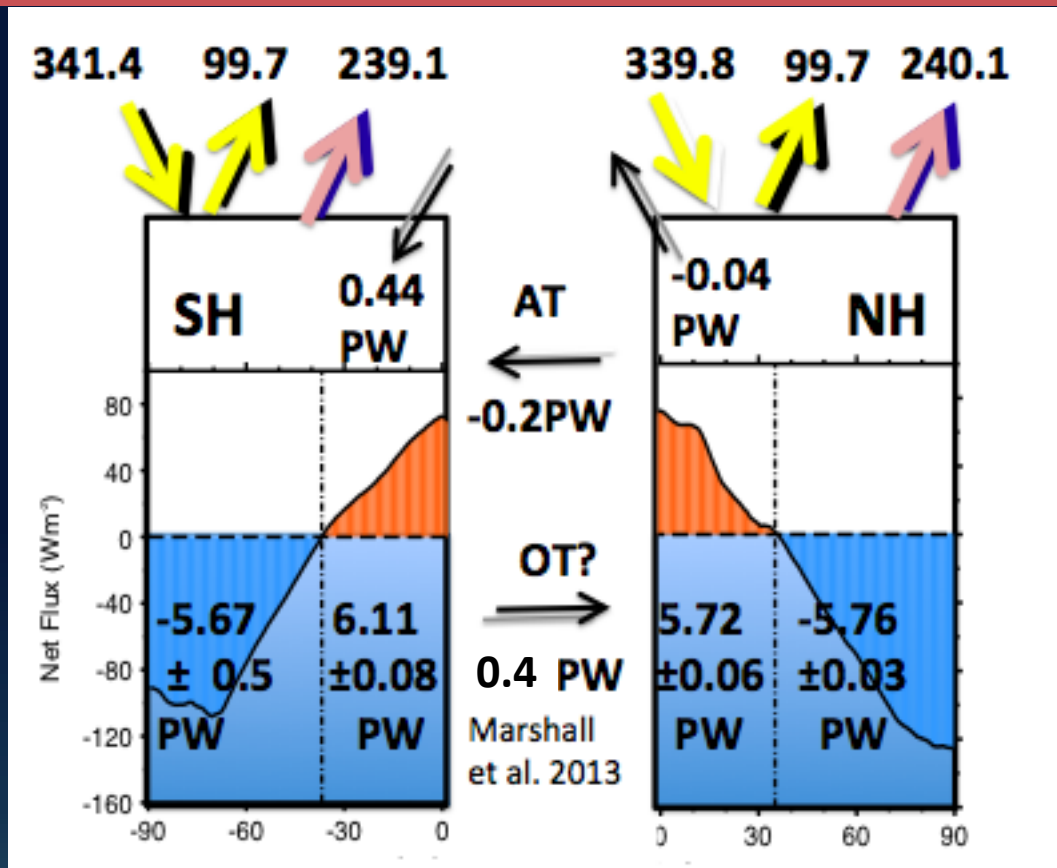
Argo data, SCRIPPS



The CERES and ARGO results are consistent in the way they point to the southern oceans as to where the heat is being absorbed. Are the data independent enough for this to be claimed robust ?



CERES EBAF



The enhanced heat uptake by the SH implies a transport across the equator to the NH to balance - this enhanced transport has to be performed by the oceans

3) Hemispheric ERB properties

$$T = \frac{F_s^\downarrow}{S} = \frac{t}{1 - r\alpha}$$

$$R = \frac{F_{TOA}^\uparrow}{S} = r + \frac{t\alpha t}{1 - r\alpha}$$

α = surface albedo

r = atmos reflection

t = atmos transmission

Data sources:

CERES EBAF2.6r Loeb et al., 2009

CERES EBAF surface fluxes,
Kato et al., 2009

CloudSat/CALIPSO

Geoprof

Box 1 | Updated energy balance

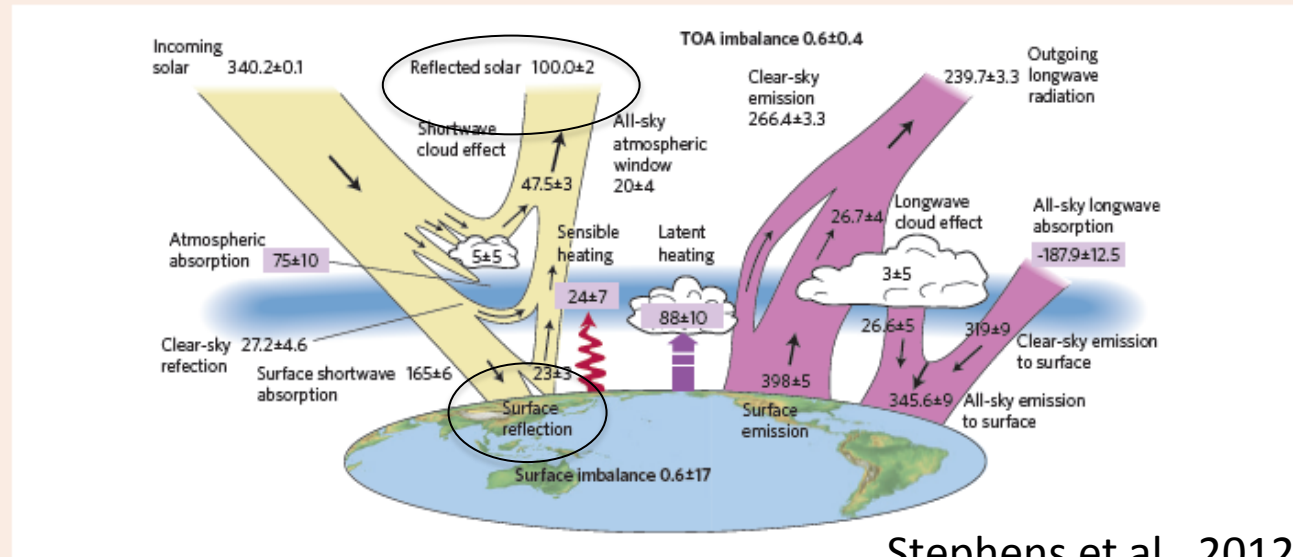
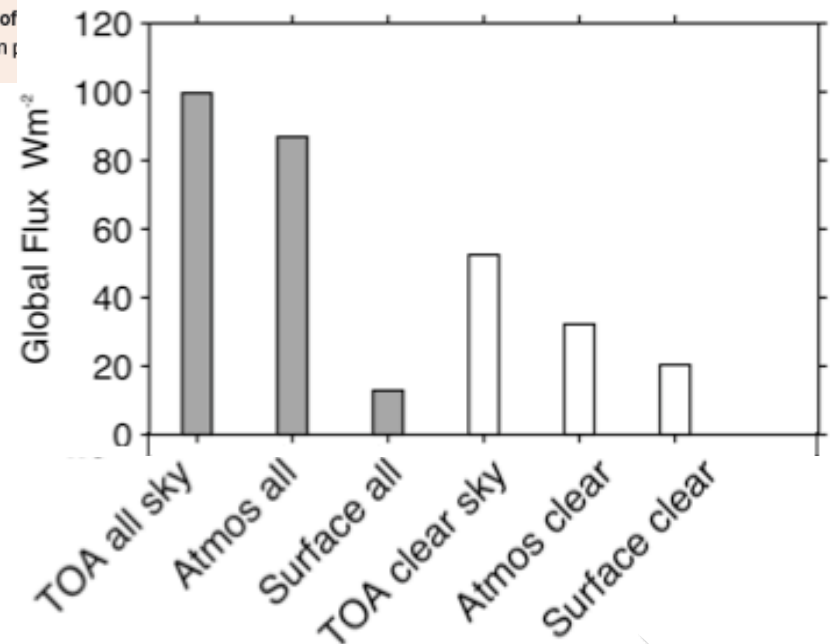


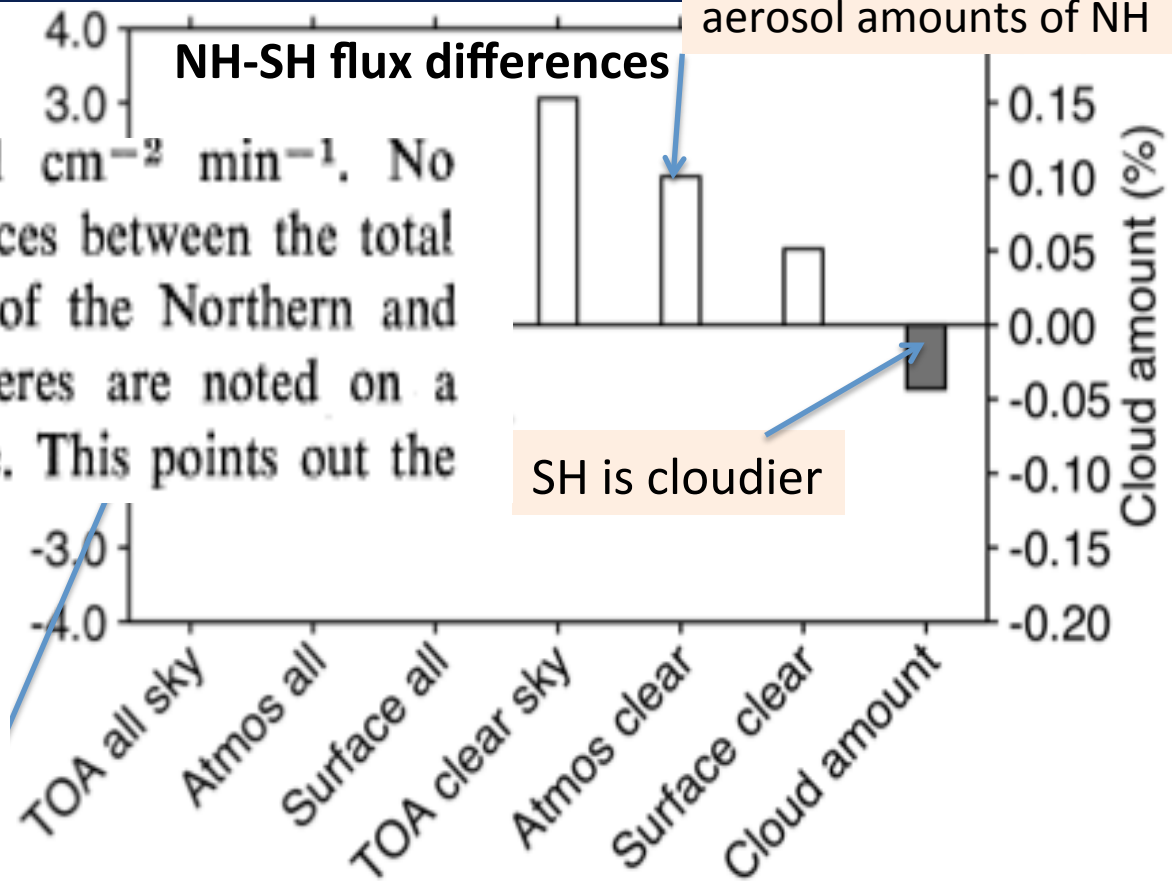
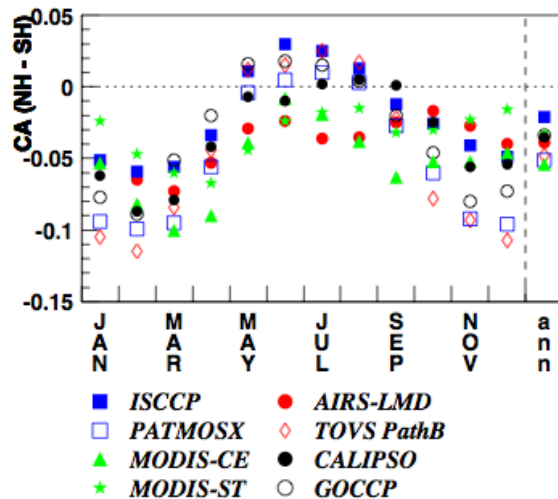
Figure B1 | The global annual mean energy budget of and infrared fluxes in pink. The four flux quantities in

Stephens et al., 2012



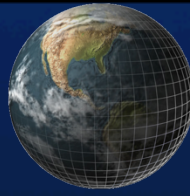
For the mean annual case, the measured global planetary albedo is 29 percent and the entire earth-plus-atmosphere system is in near radiative equilibrium since the incoming solar radiation averages 0.33 cal cm⁻² min⁻¹. No significant differences between the total radiation budgets of the Northern and Southern hemispheres are noted on a mean annual scale. This points out the

Vonder Haar & Suomi, 1969



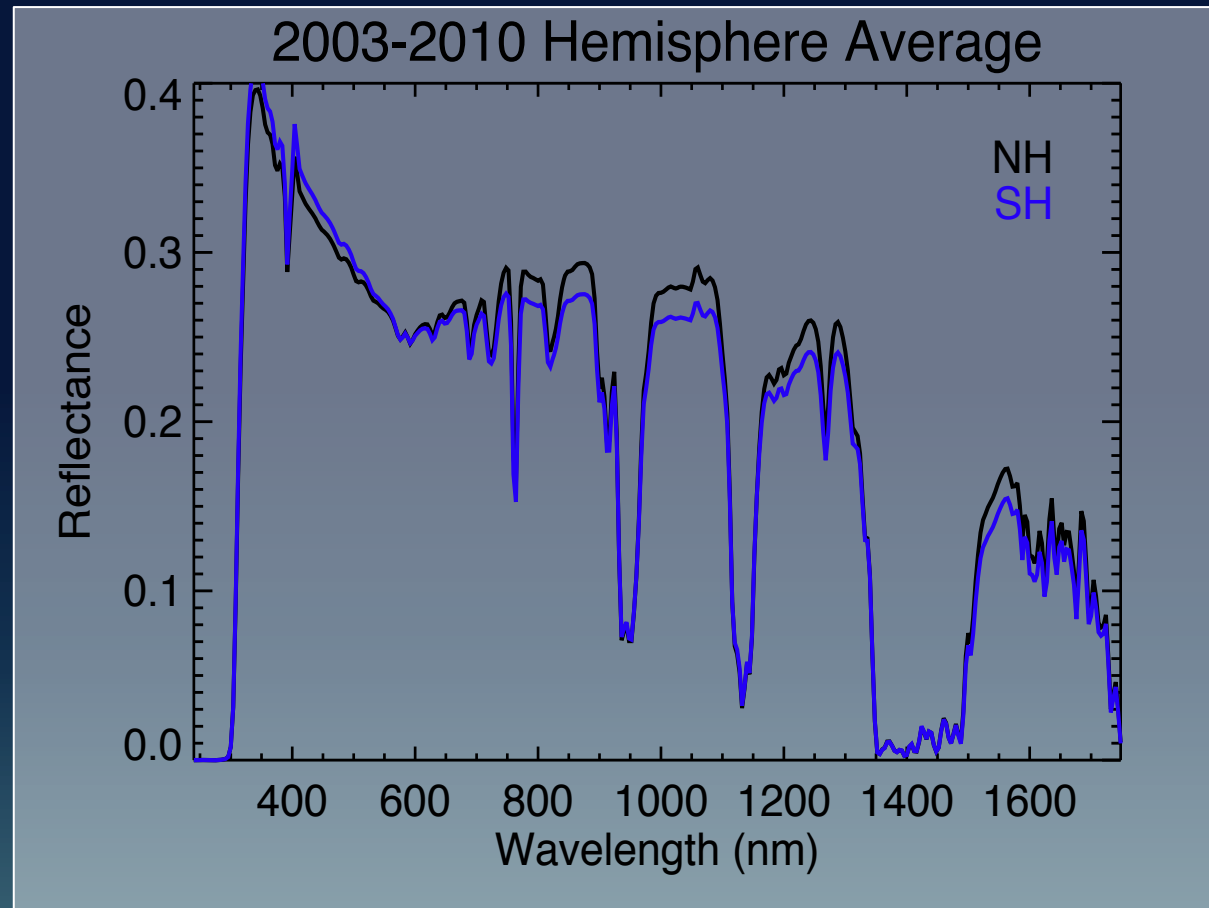
Although the hemispheres are structurally different, the reflected flux is identical ($\sim 0.1 \text{ Wm}^{-2}$) – Vonder Haar and Suomi, 1969; Voigt et al., 2012; Stephens et al 2014

A little more anecdotal evidence



Although the total energy reflected by each hemisphere is the same, the spectral differences clearly show compensating effects of land and clouds

SCHIAMARCHY DATA

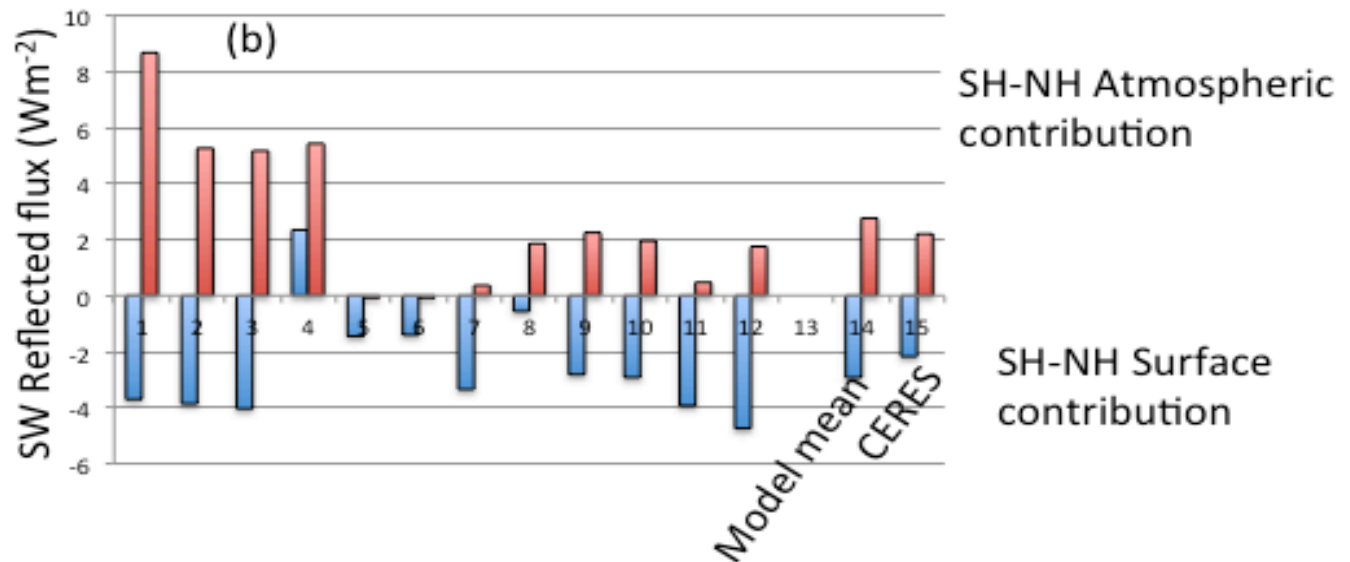
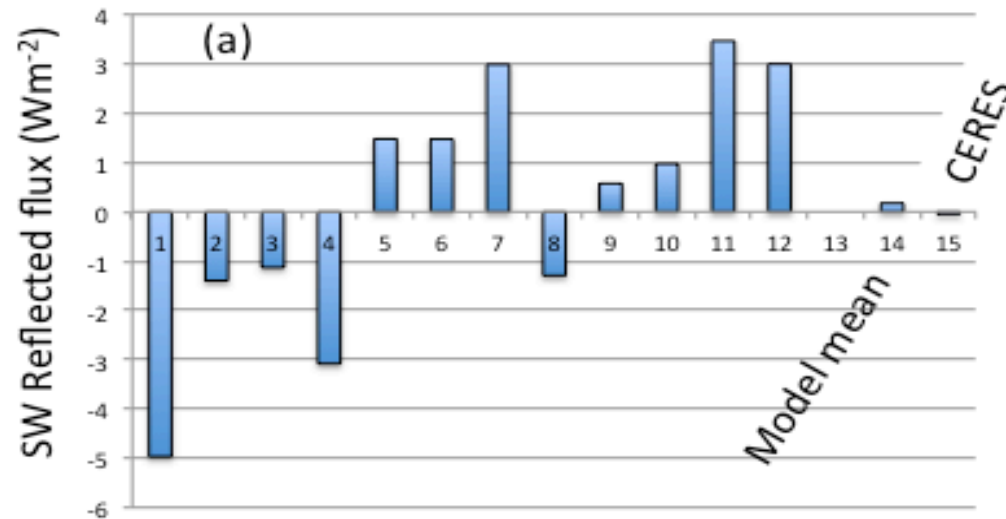


Stephens et al., 2014



CMIP5 analysis

NH-SH



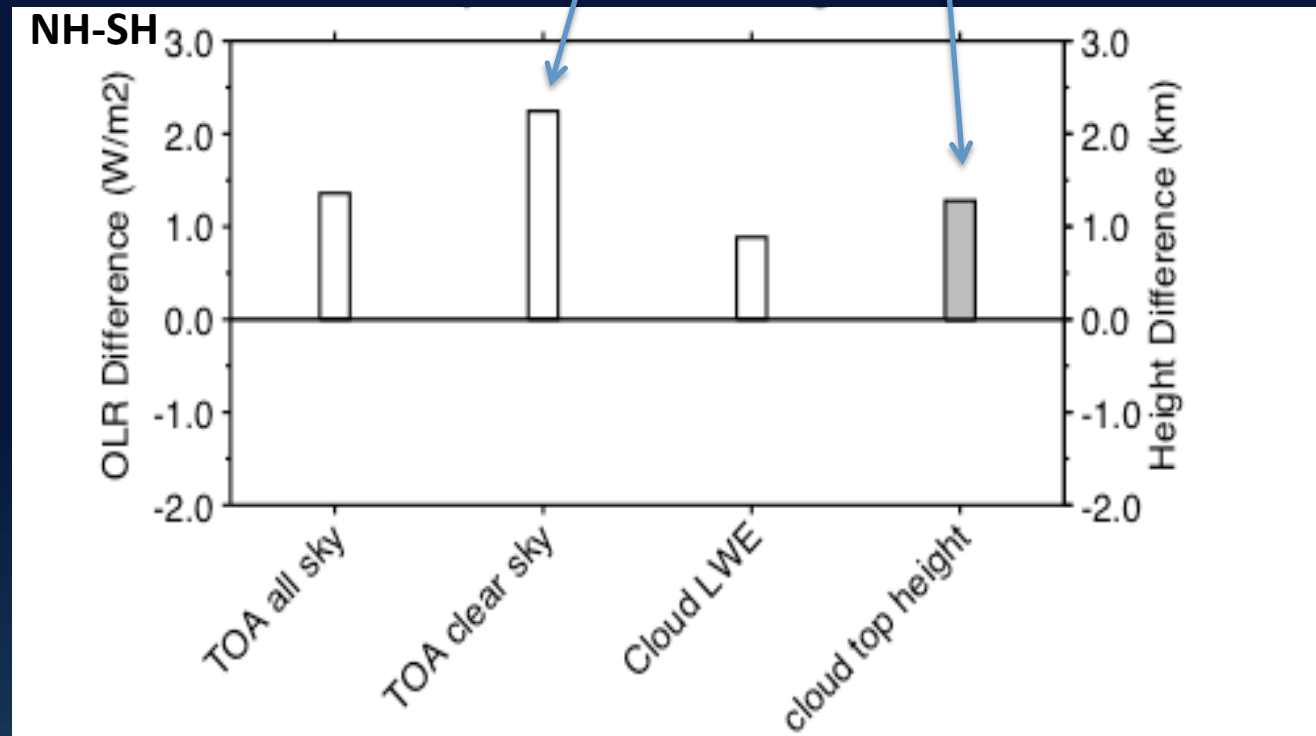
- 1) There is a general lack of hemispheric symmetry in models
- 2) The reasons for this vary – in some models the SH clouds are too bright, for others clouds aren't bright enough & yet in others the surface is too bright

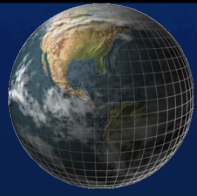
The OLR



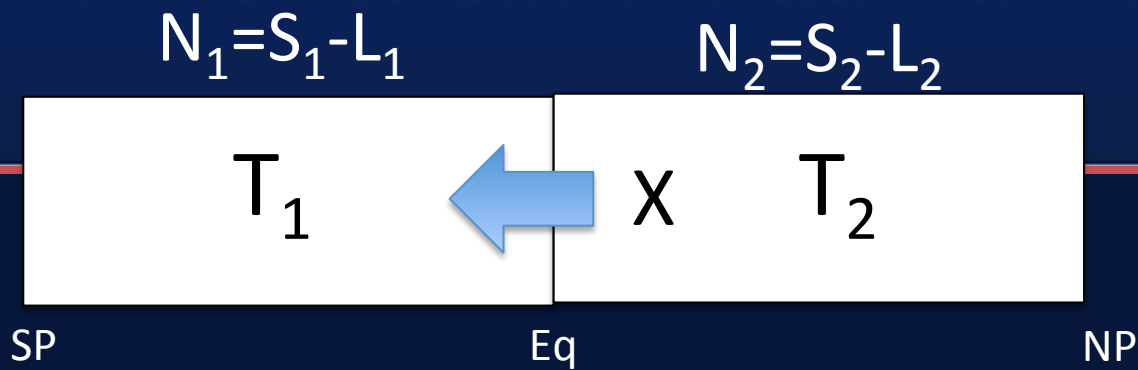
Much of the clear-sky differences (warmer NH) offset by higher (colder) NH cloud tops

The OLR is not as symmetric. The SH emits less to space than the NH and it is in the SH that the heat imbalance is realized. Clouds provide the degrees of freedom that establish the near hemispheric symmetry both in reflected sunlight and OLR.





Interpretation of symmetry



In a balanced, steady state

$$N_1 + N_2 = 0 \quad (1)$$

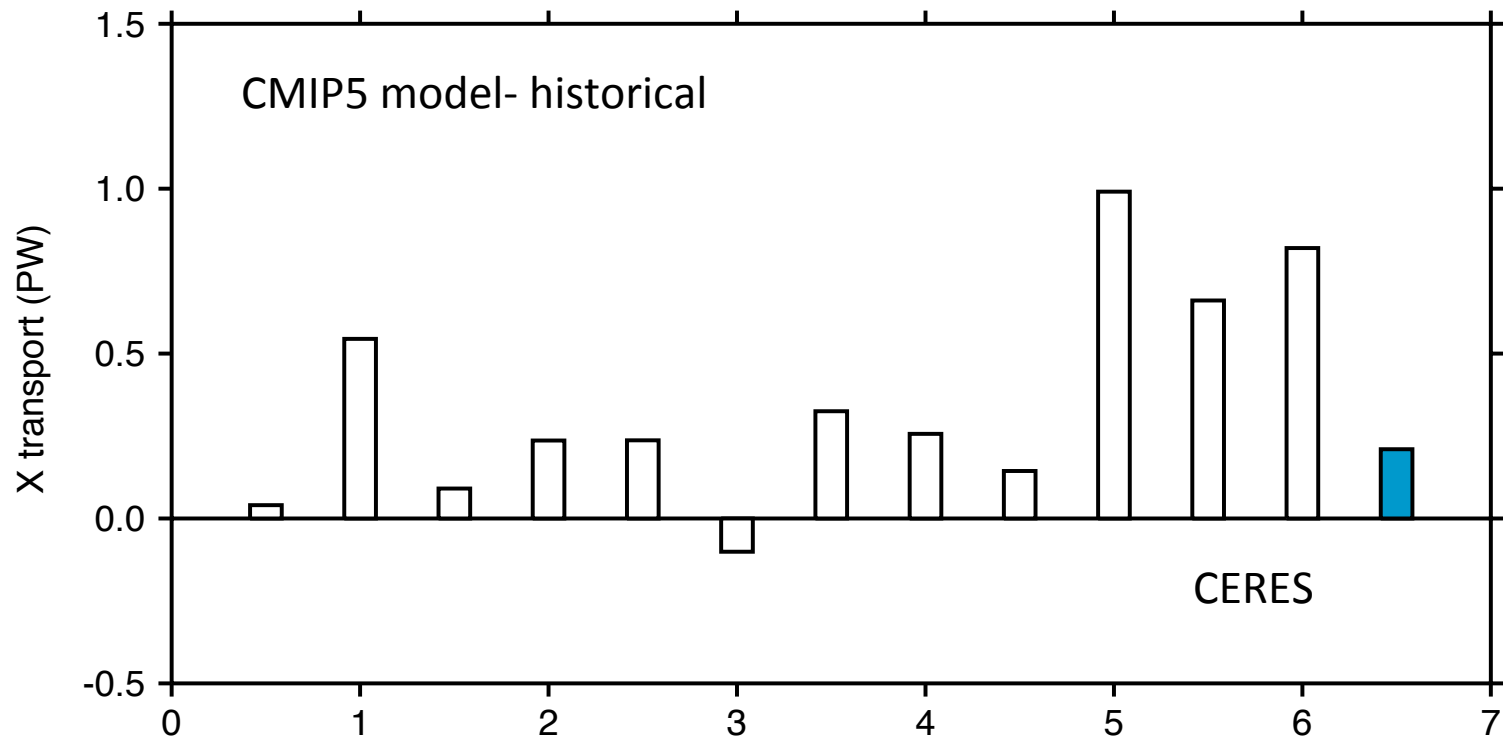
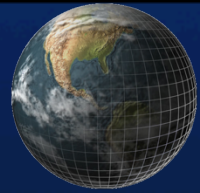
where $N_1 = S_1 - L_1 = X$ and $N_2 = S_2 - L_2 = -X$

In the special case of $X=0$ then $N_1=N_2=0$ and $L_1=L_2$ otherwise a thermodynamic force is implied that induces $X \neq 0$.

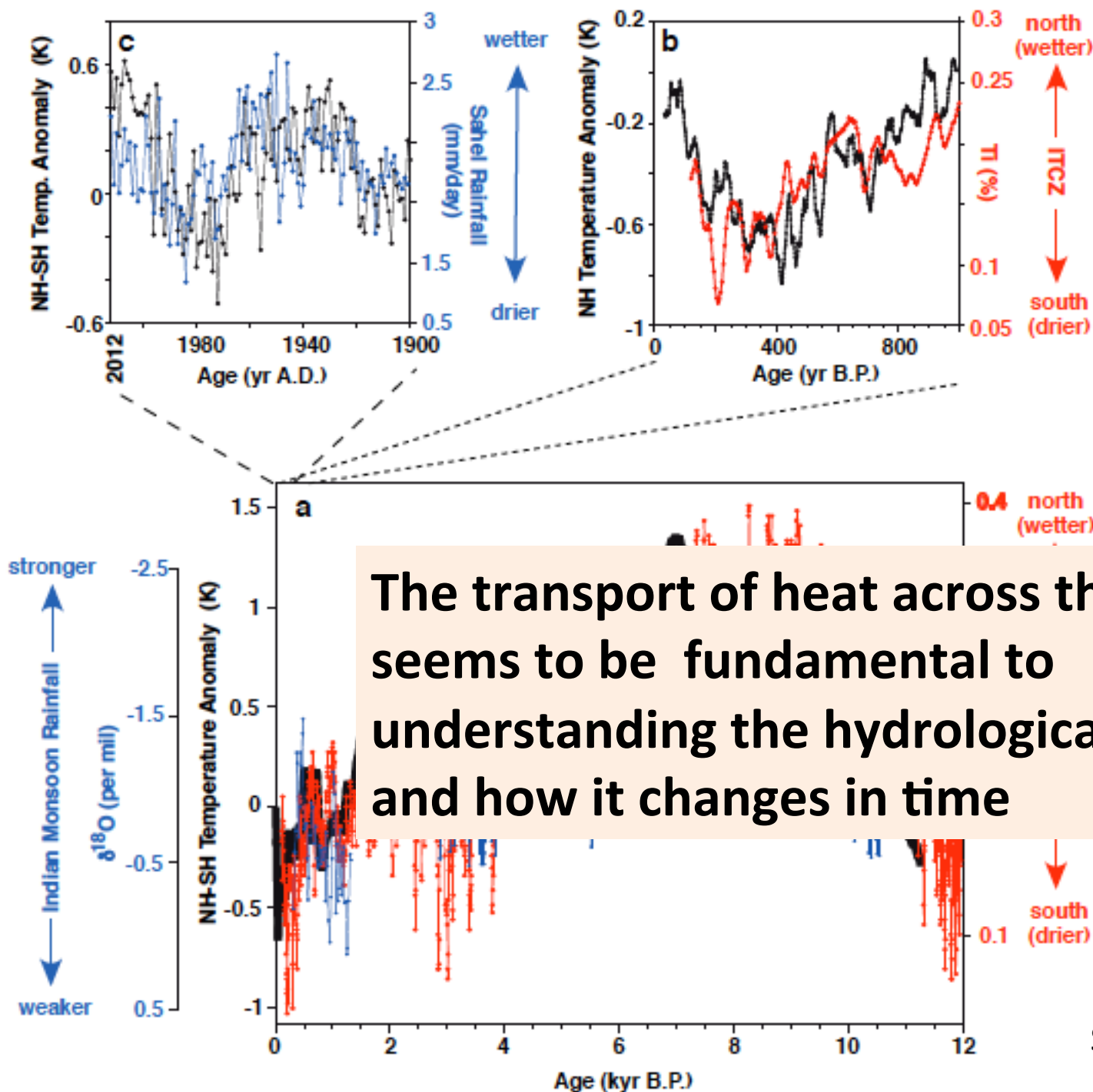
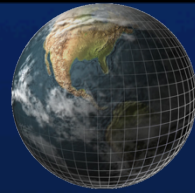
In this case $S_1=S_2$

Thus a precise symmetry occurs when $X=0$.

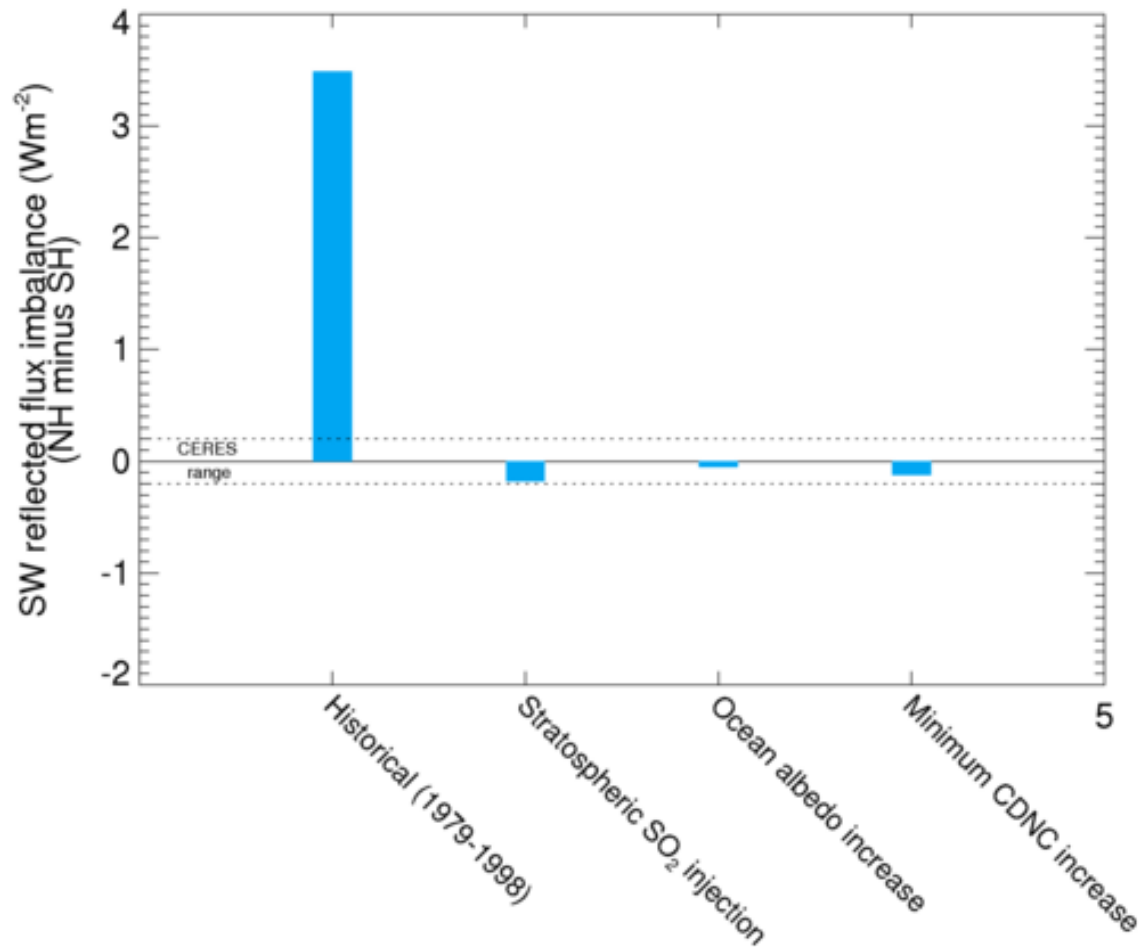
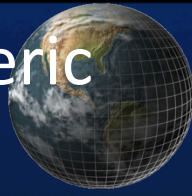
Cross equatorial transport



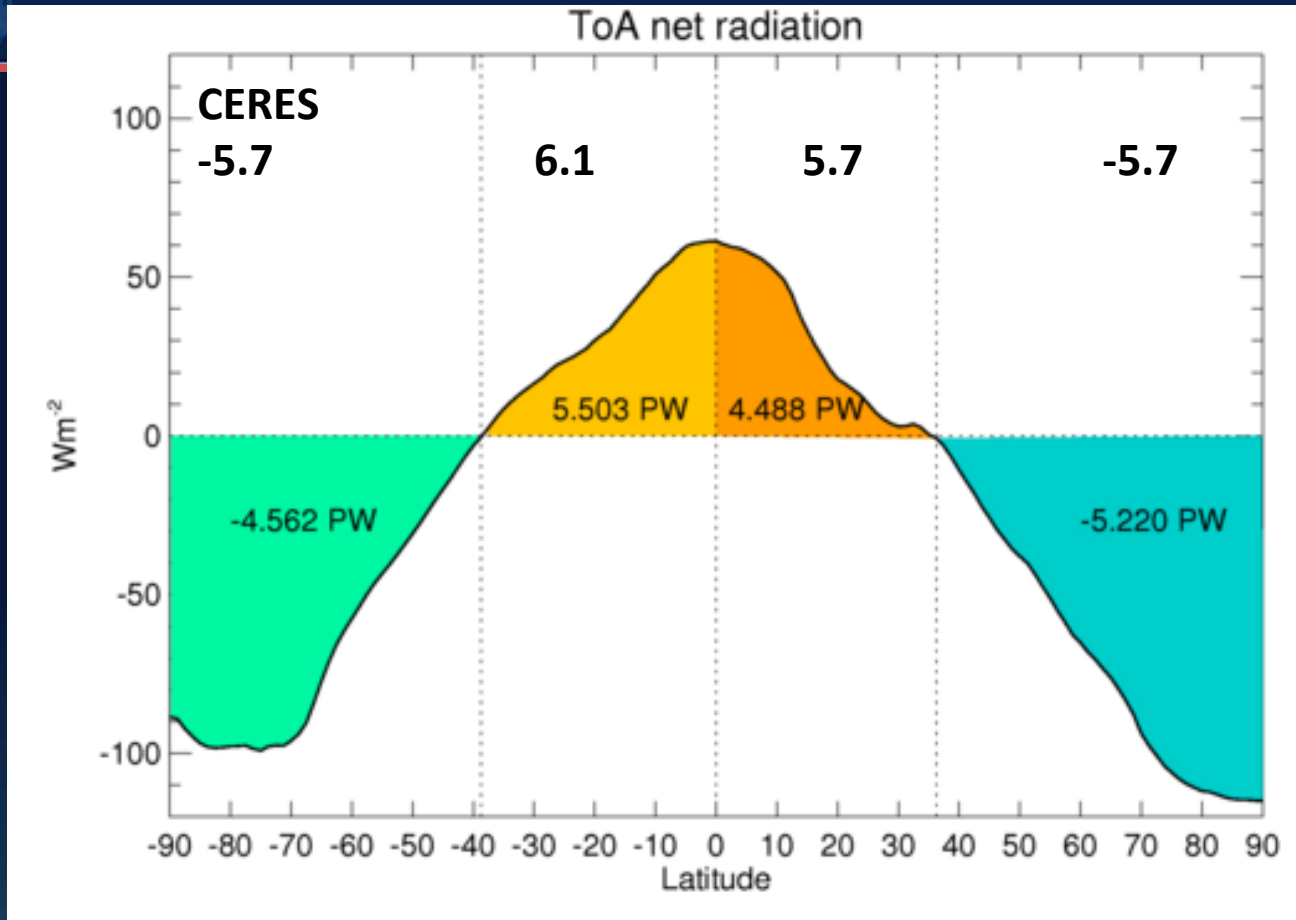
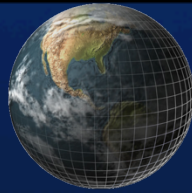
There is ~ an 8-fold difference in X between CMIP5 models and up to a 4-fold difference wrt CERES



Experiments with HadGEM to equilibrate hemispheric albedo (Haywood et al, 2014 in prep)



HadGEM, CMIP5 historical, average 1979-1998-



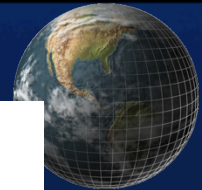
G4-SH -4.8
 CDNC(SH) -5.0
 Ocean Albedo -4.7

4.8
 5.1
 4.6

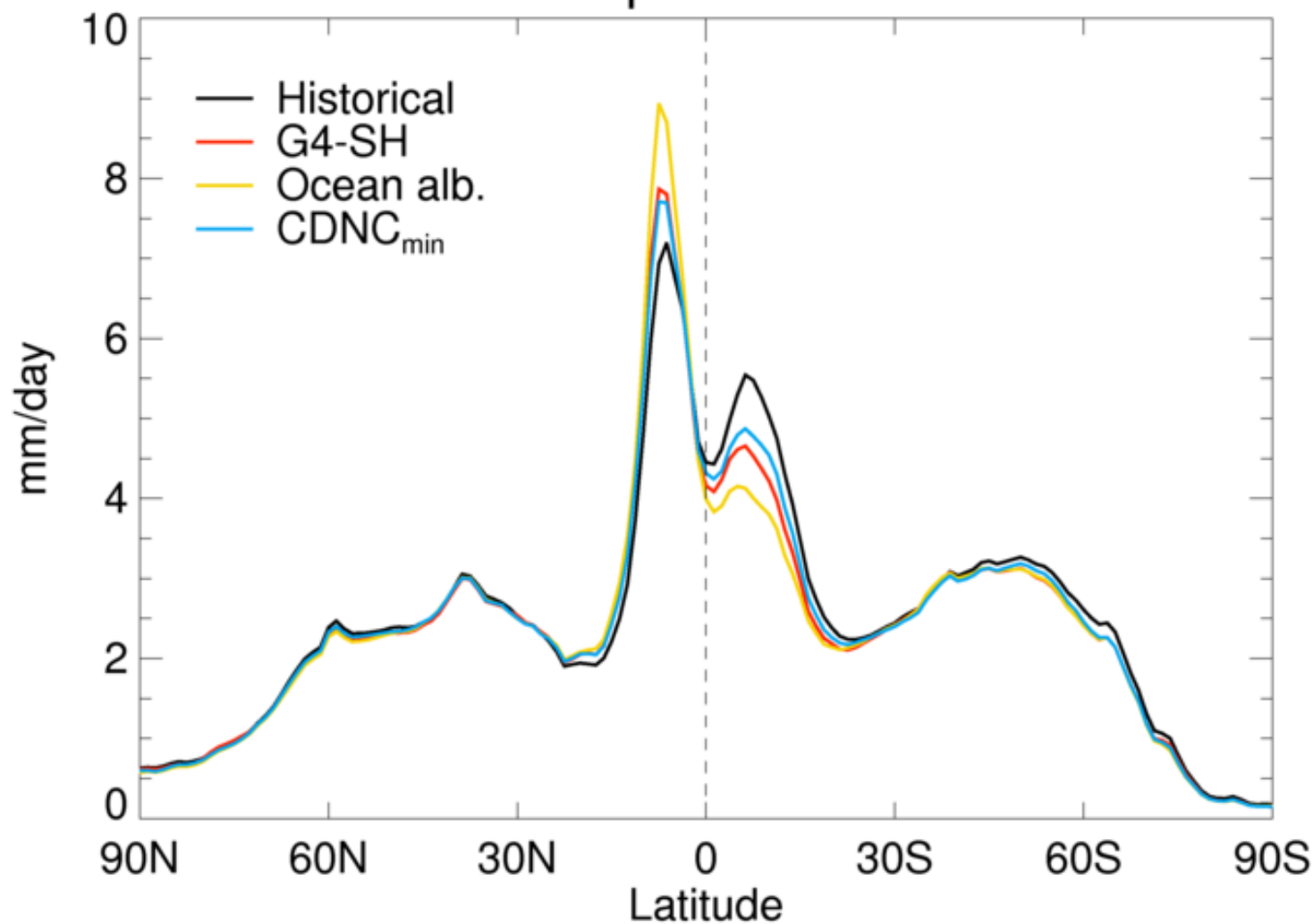
4.6
 4.7
 4.9

-5.2
 -5.2
 -5.1

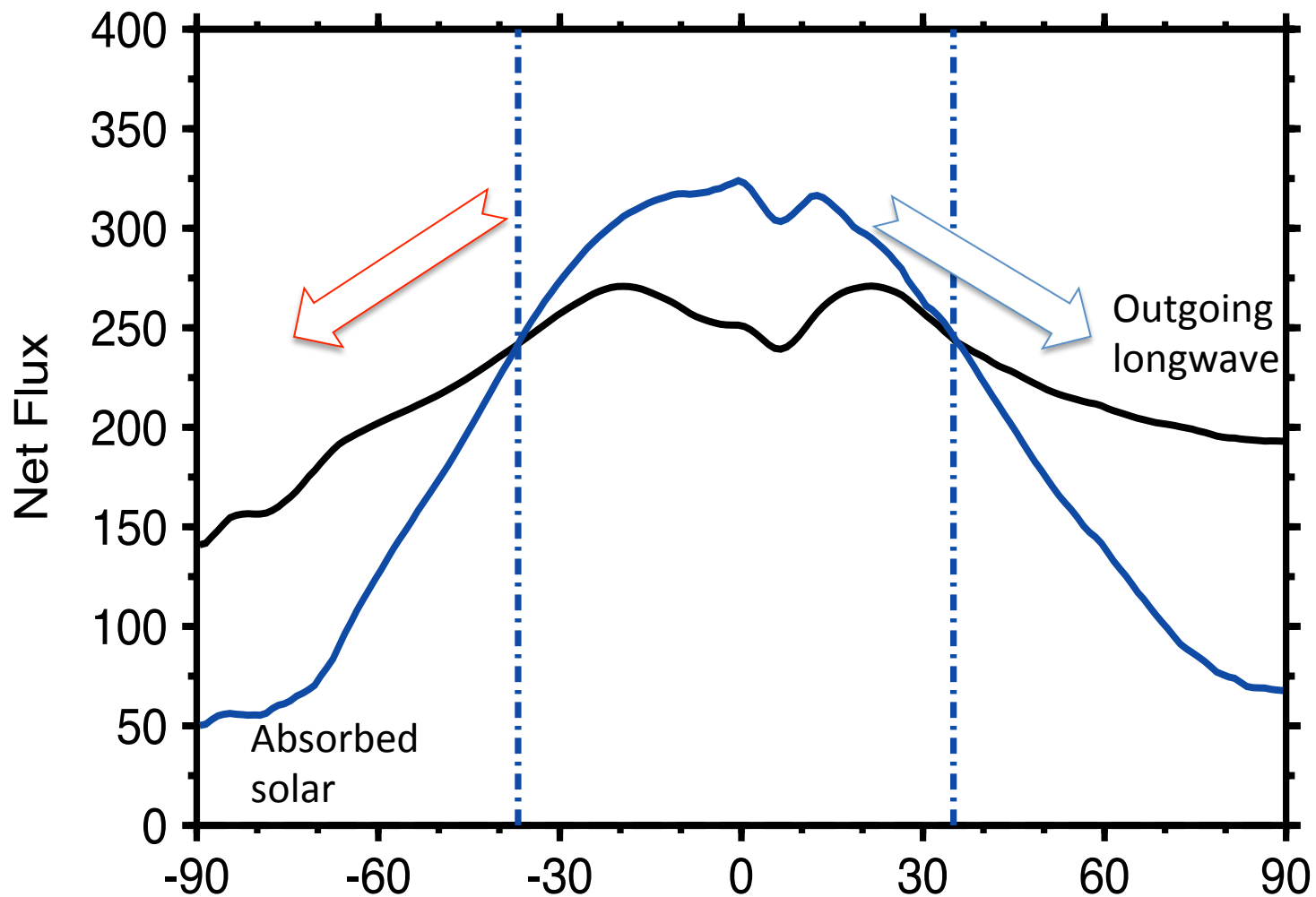
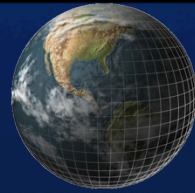
X (PW)
 0.8
 0.4
 0.4
 0.4



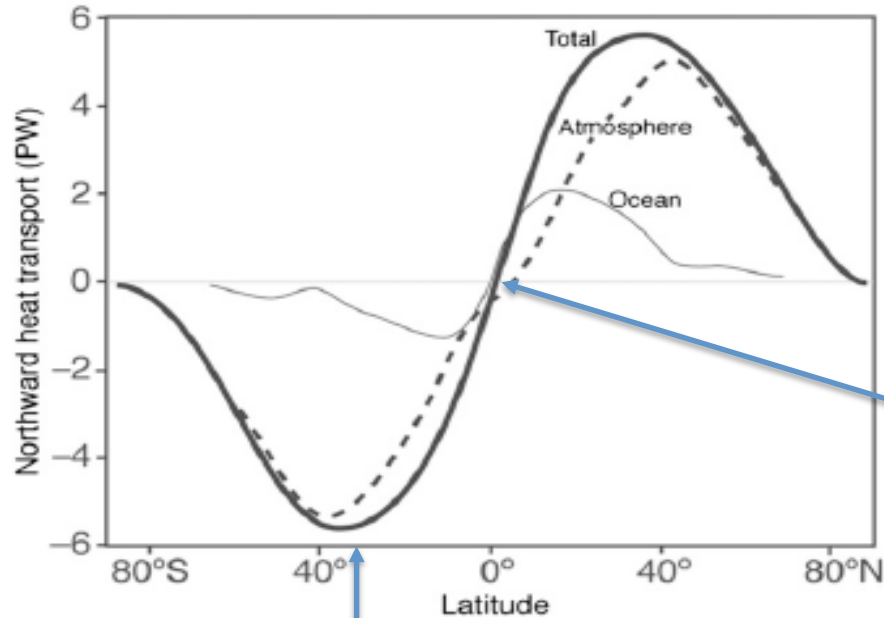
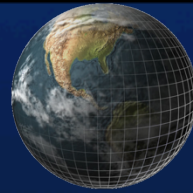
Precipitation rate



4) Differential heating equ-pole and the meridional heat transport

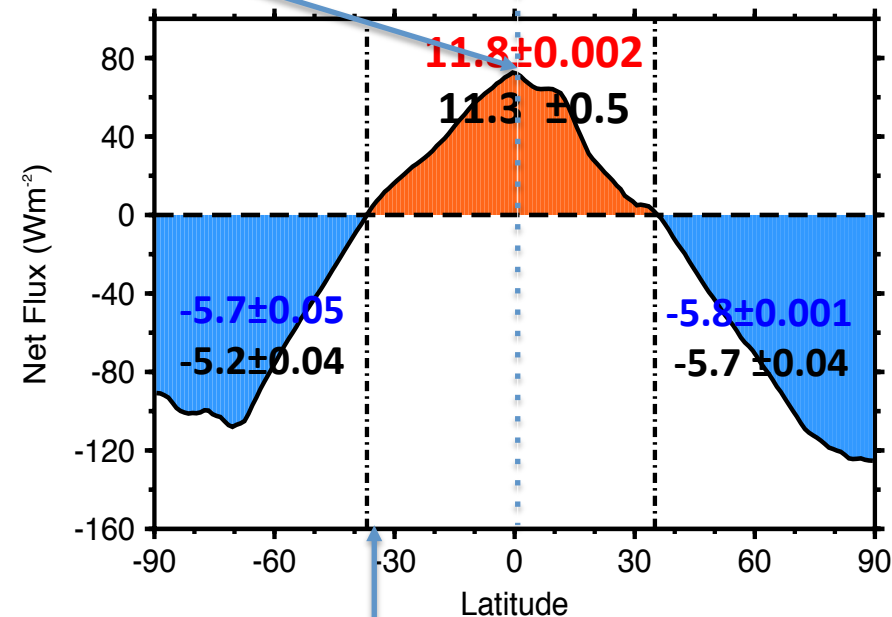


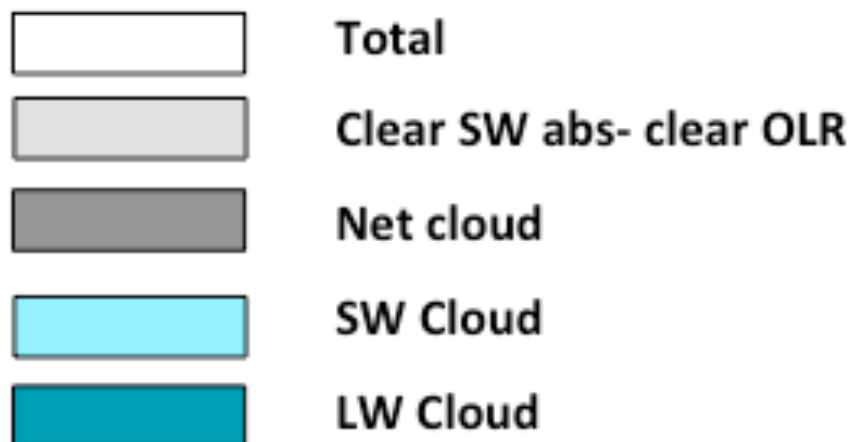
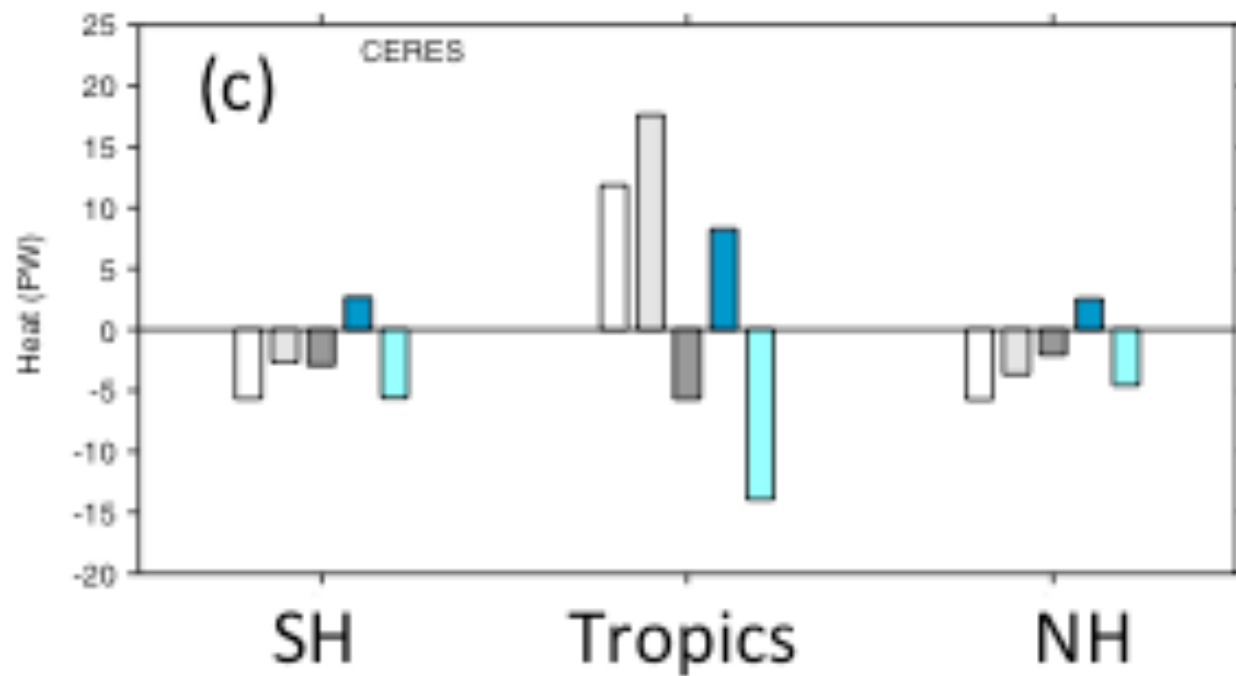
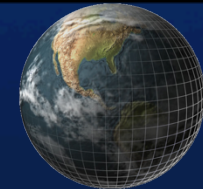
Properties of transport inferred from TOA net flux



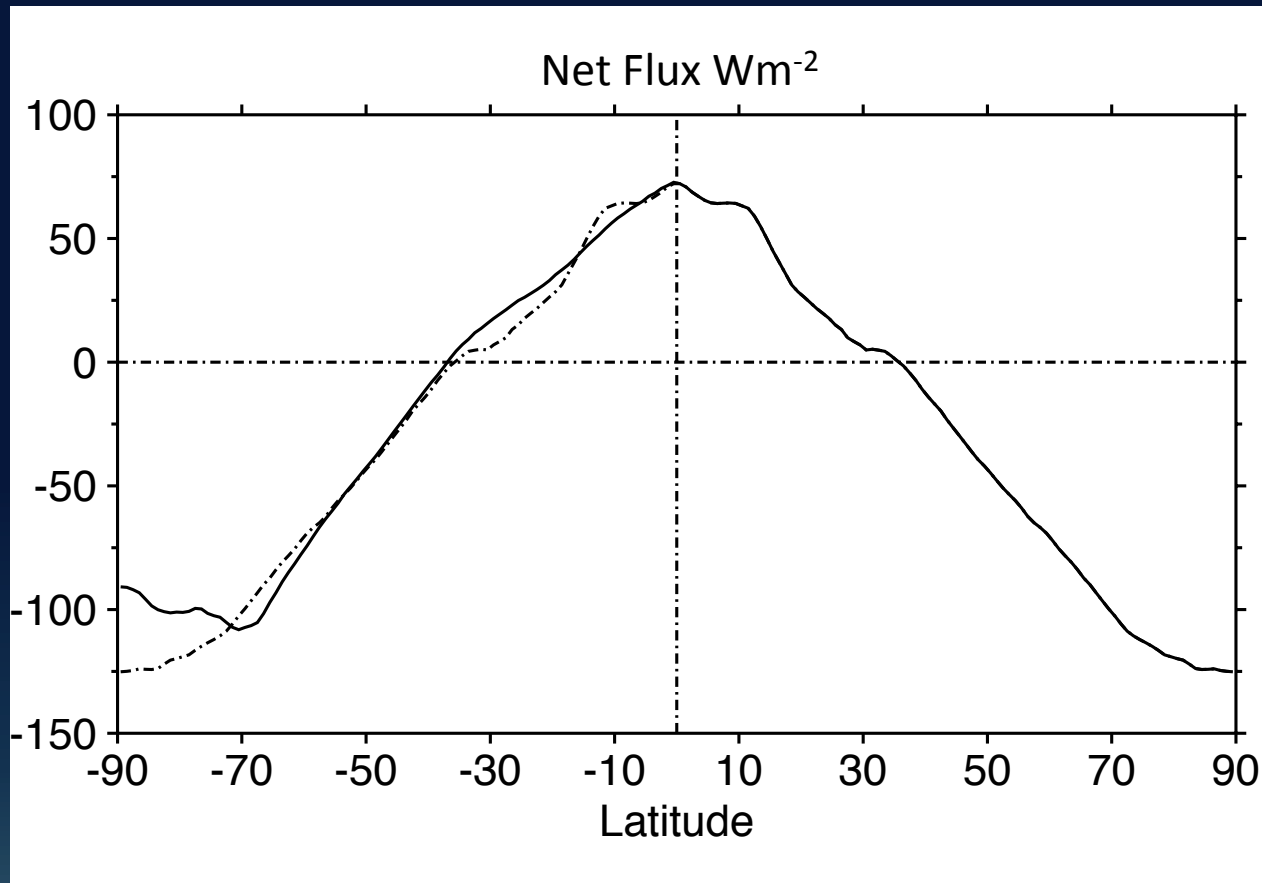
Latitude of maximum net flux maximum of zero transport

Latitude of maximum transport

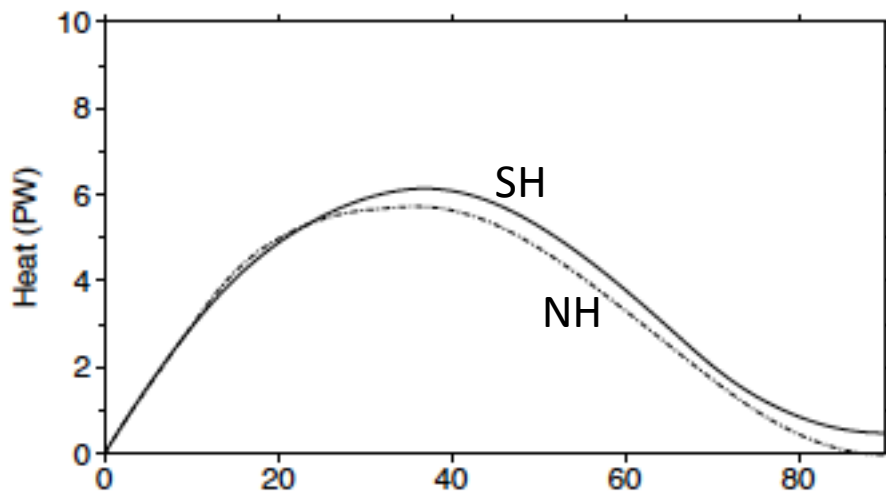
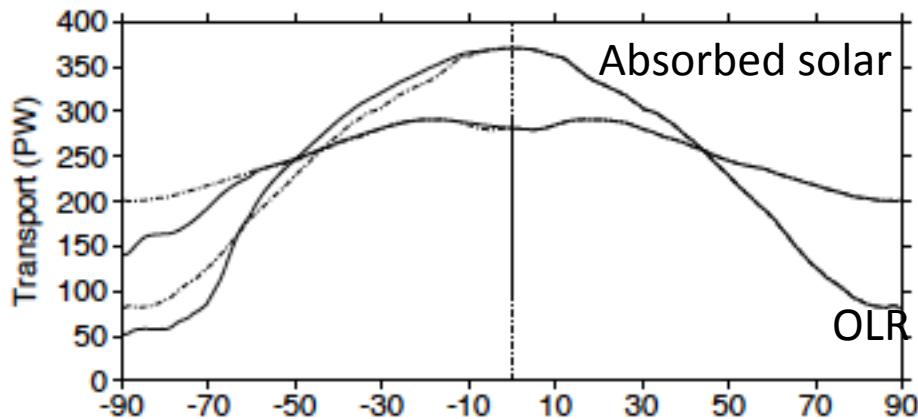
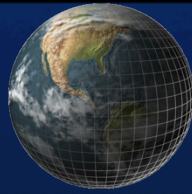




A basic question to ask is 'what mechanisms produce the heat differential between hemispheres?'



A CERES view of SH heating



Summer latitude

The increased heating of the SH is occurring mostly between 20-40S and seems to be associated with an increased absorbed solar

5) The WCRP clouds/climate grand challenge

Q1: How will storm tracks change in the future?

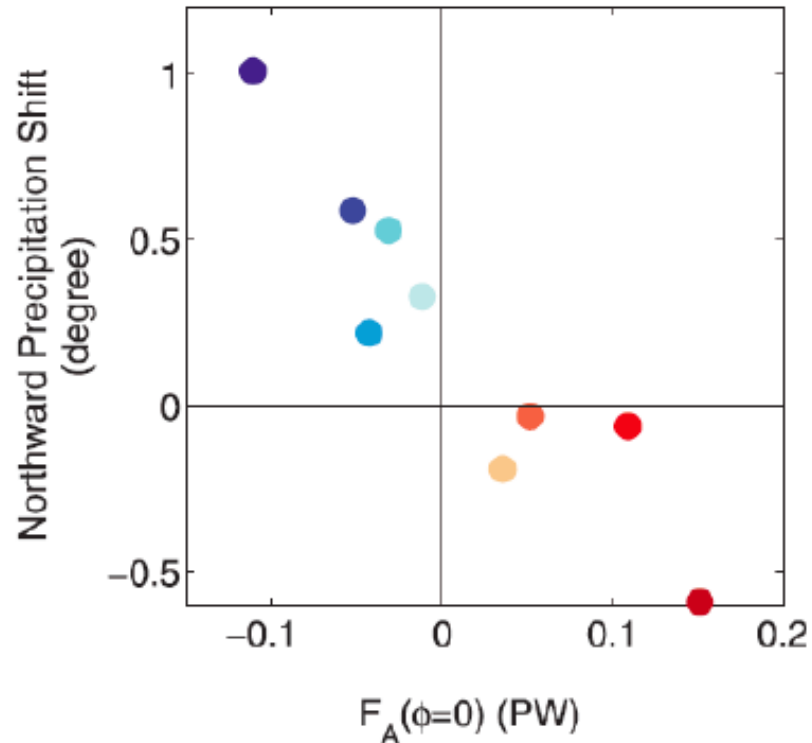
Q2: What controls the position and strength of tropical convergence zones?

Q3: Is convective aggregation important for climate?

Q4: How does convection contribute to cloud feedbacks?

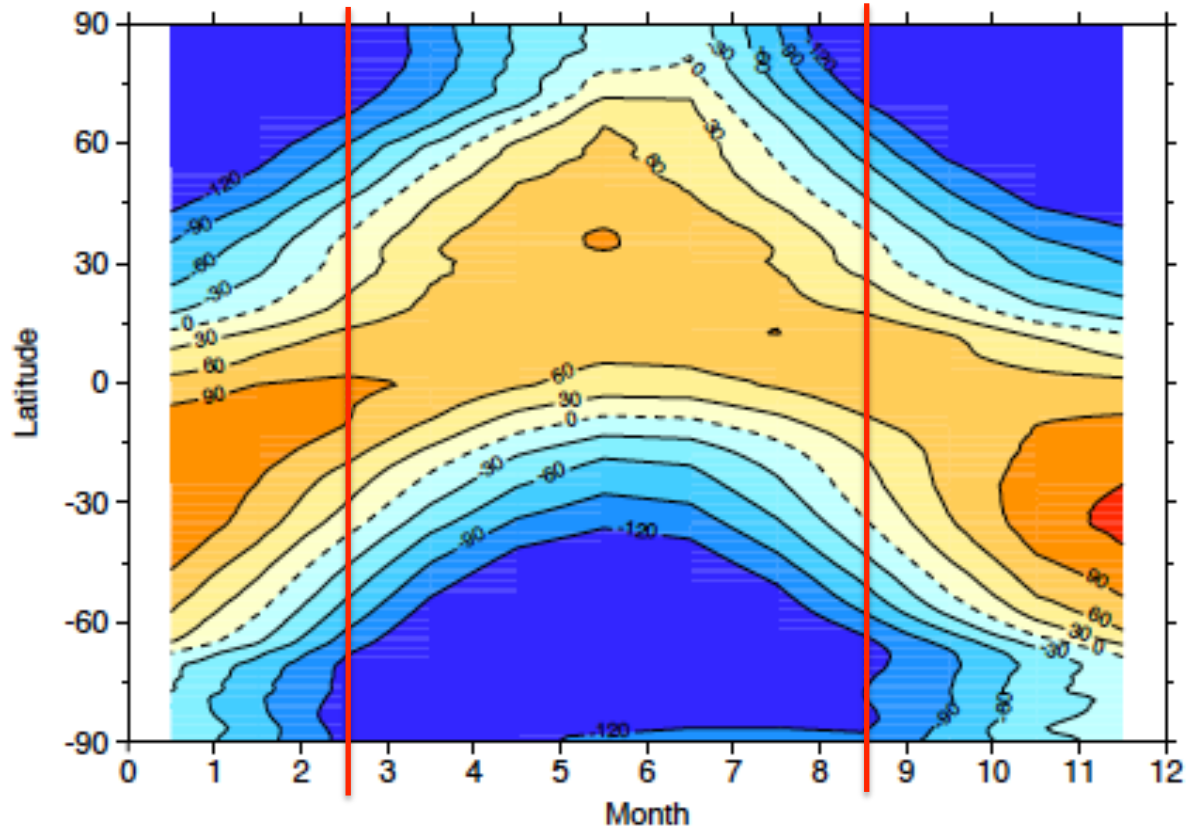
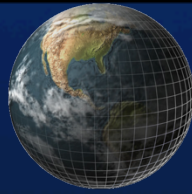
What of ERB controls?
Inspiration drawn from
a series of Riehl &
Malkus studies

Kang et al., 2009



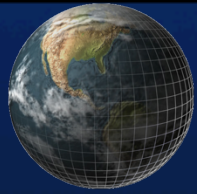
equatorial inter-hemispheric energy transport

Seasonal balances



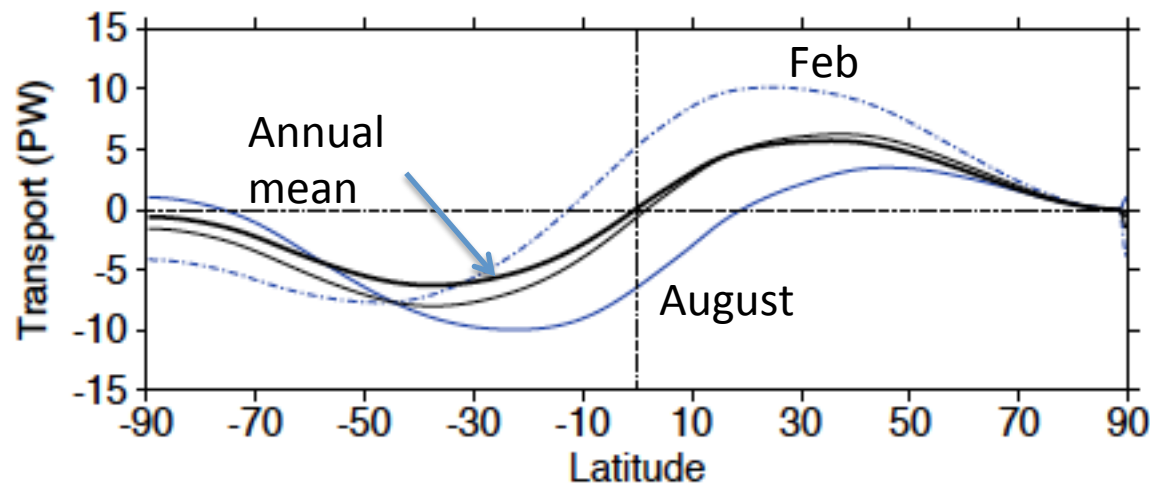
THESE ARE THE TIMES WHEN THE SST CHANGES ARE MINIMUM

Seasonal balances

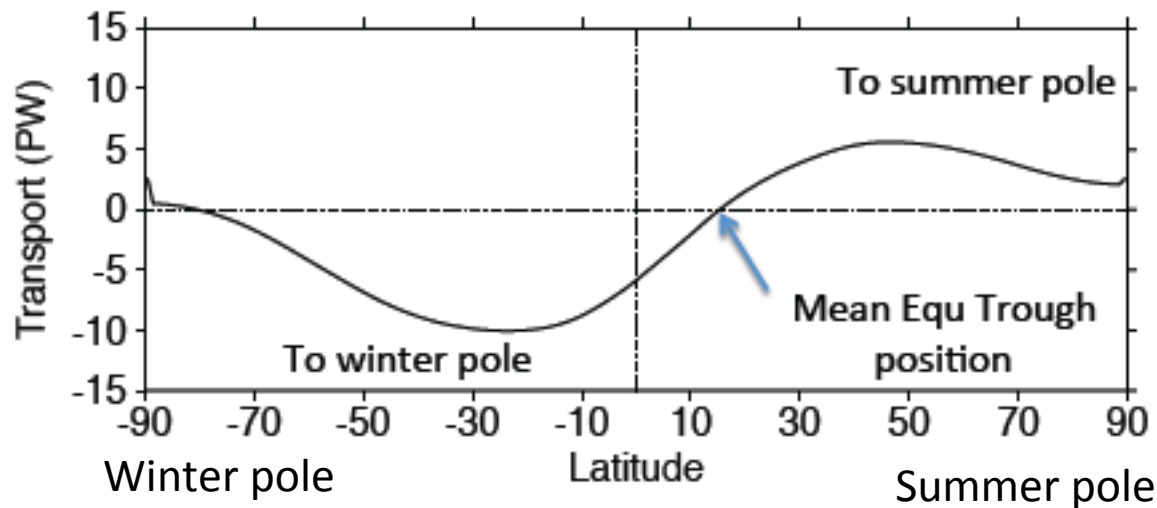
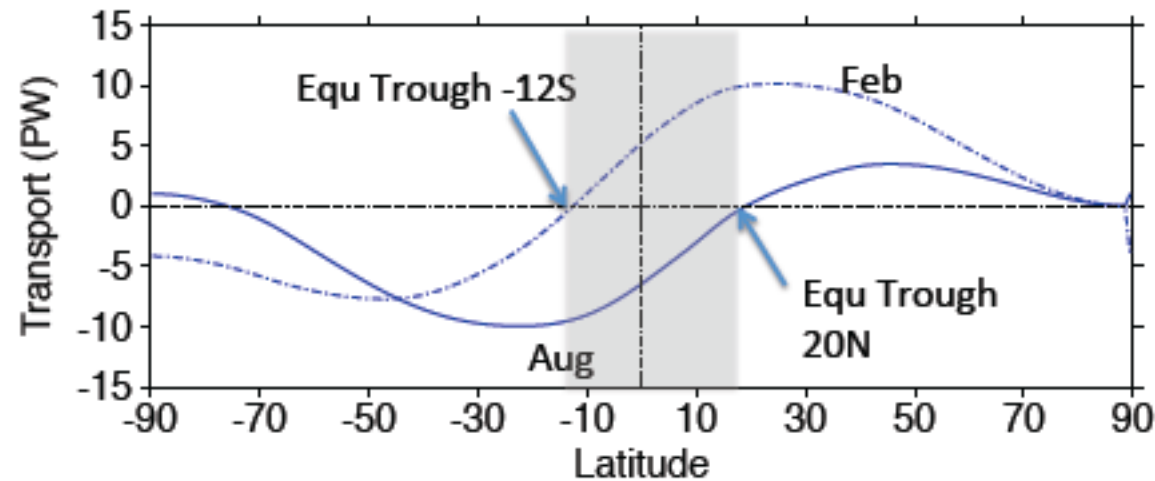
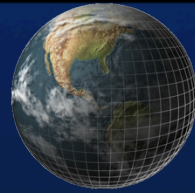


Any attempt to determine the seasonal transports of heat from low latitudes to high latitudes has to deal with the storage of heat by the oceans.

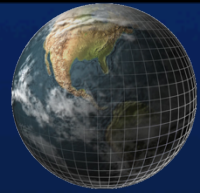
There are times when ocean heating is zero, such as occur when tropical ocean temperatures (SSTs) are at their max or min (late February, late August). ERB- based transports calculated at these times thus reflect true transport of the system. A test is the average of these transports derived at these times ought to be equivalent to the annual mean.



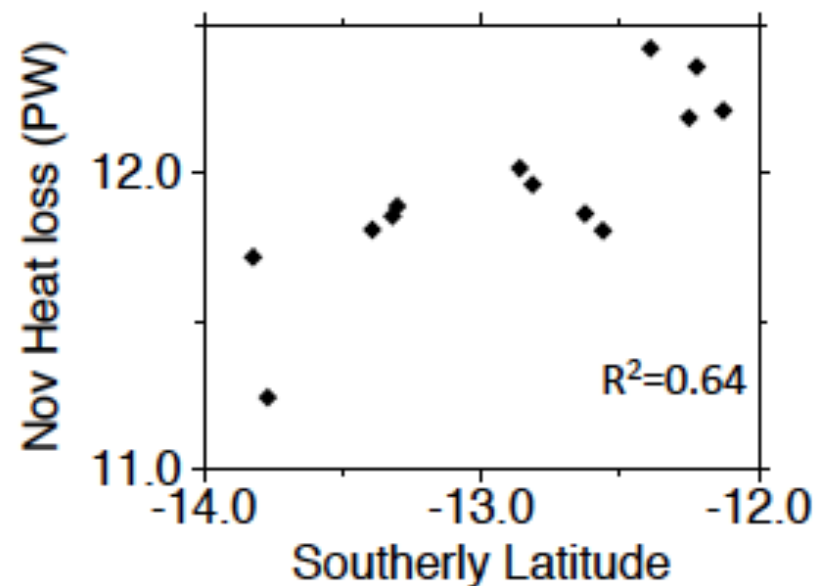
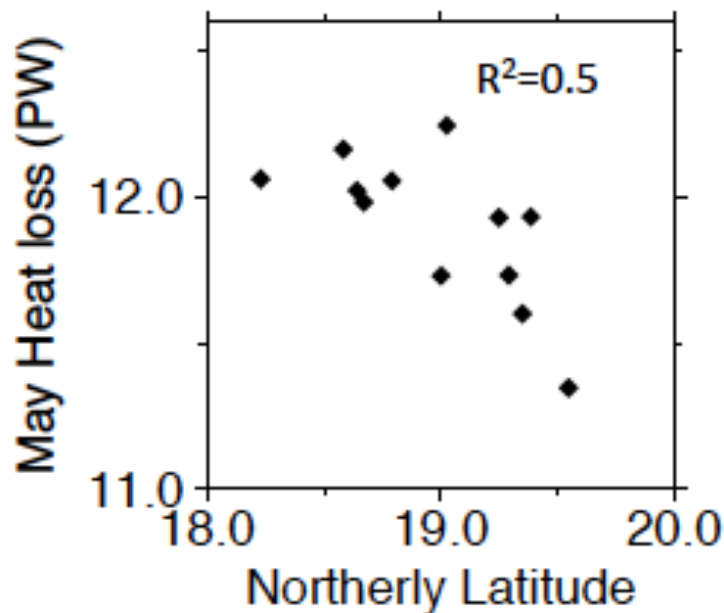
The tropical trough divides the energy transport between summer and winter poles



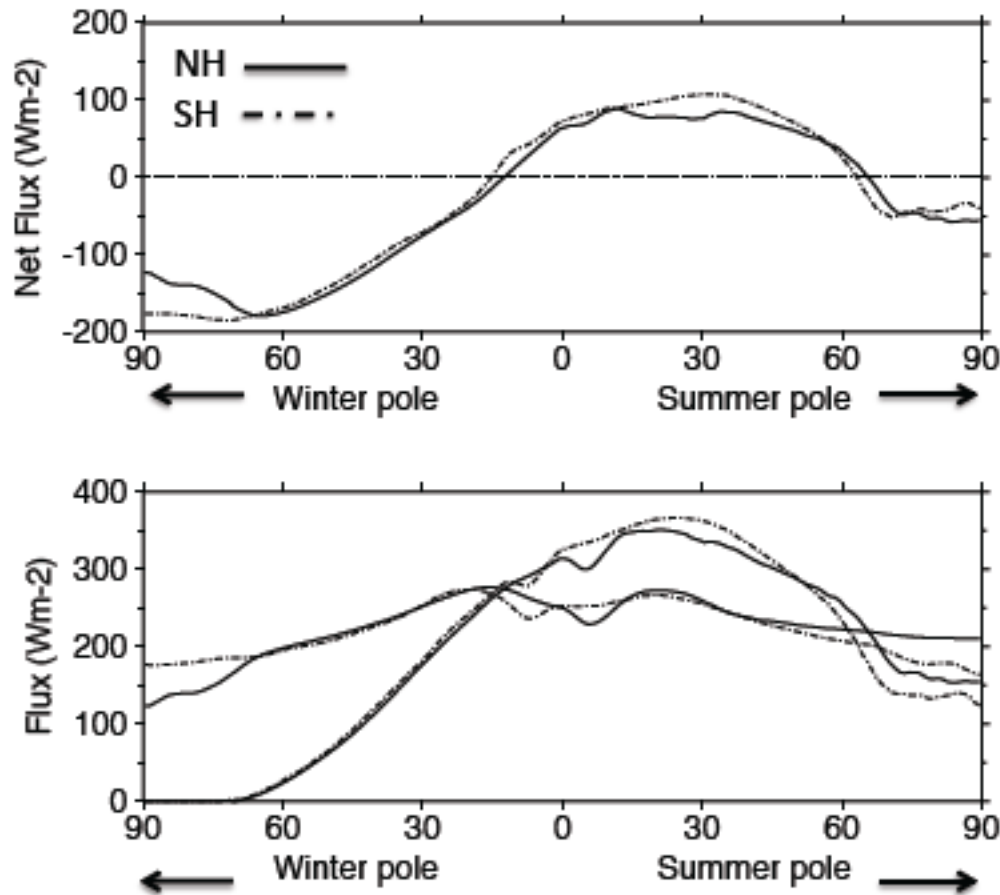
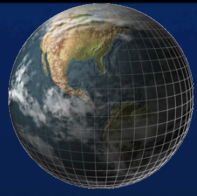
Defines the equatorial region from which heat is always transported to the winter pole (Riehl & Malkus)



From this perspective, the latitudinal limits of the trough zone is determined by how much energy is transported to the winter pole. The NH bias in the position of this zone is set by seasonal asymmetries of the energy balance.

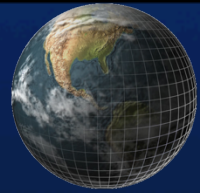


Seasonal energy balances



While many hypothesis are offered to explain why the ITCZ climatologically exists in the NH, the energy balance argument says it exists as a consequence of differential incoming solar into the respective summer seasons.

Summary



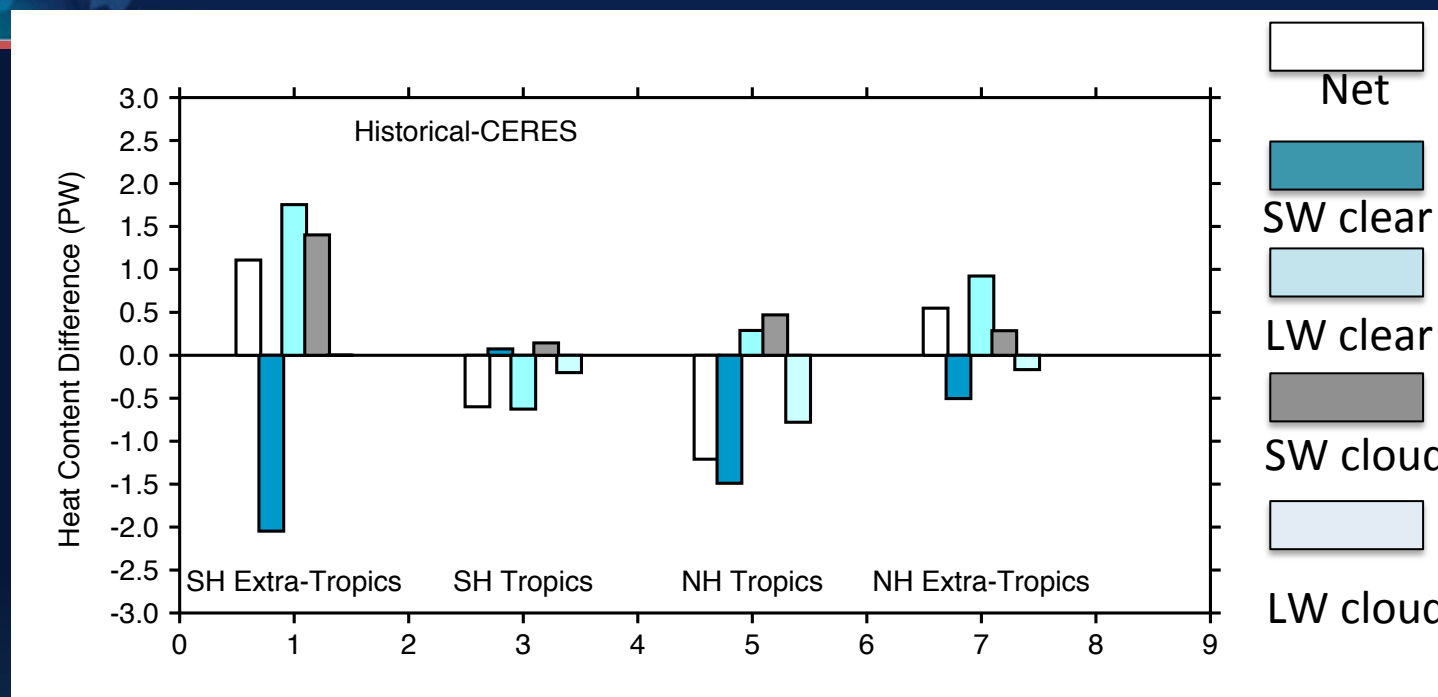
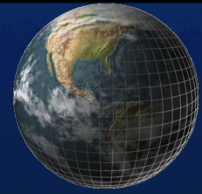
averages $0.33 \text{ cal cm}^{-2} \text{ min}^{-1}$. No significant differences between the total radiation budgets of the Northern and Southern hemispheres are noted on a mean annual scale. This points out the

- (i) Actually there is a slight asymmetry –in the OLR.
- (ii) The SH is gaining heat mostly in the subtropical zone

(iii) This implies an enhanced transport of heat from the SH to NH through the oceans

(iv) There is ~ an 8-fold difference in X between CMIP5 models and up to a 4-fold difference wrt CERES and this transport difference seems to matter to tropical convergence zones and precipitation patterns

(v) Tropical convective zones occur in the tropical trough regions, the positions of which are defined by winter energy losses and the amount of absorbed sunlight in the summer tropics



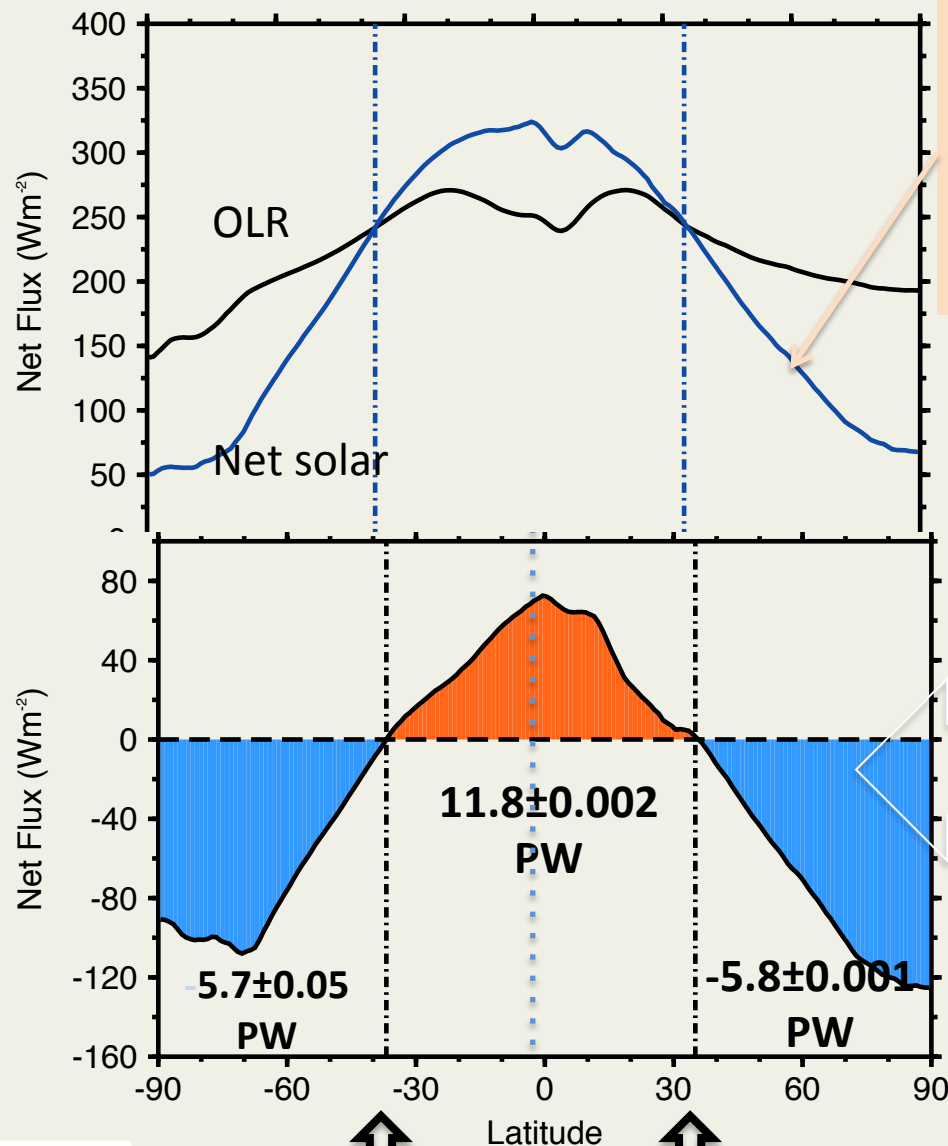


Lat of max
transport

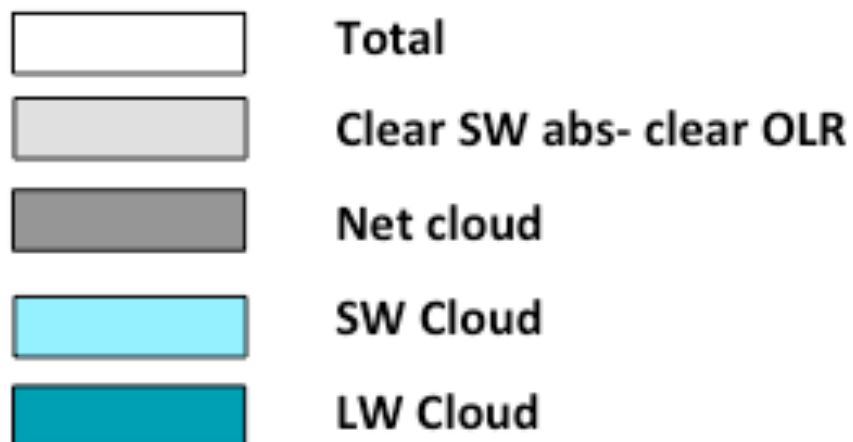
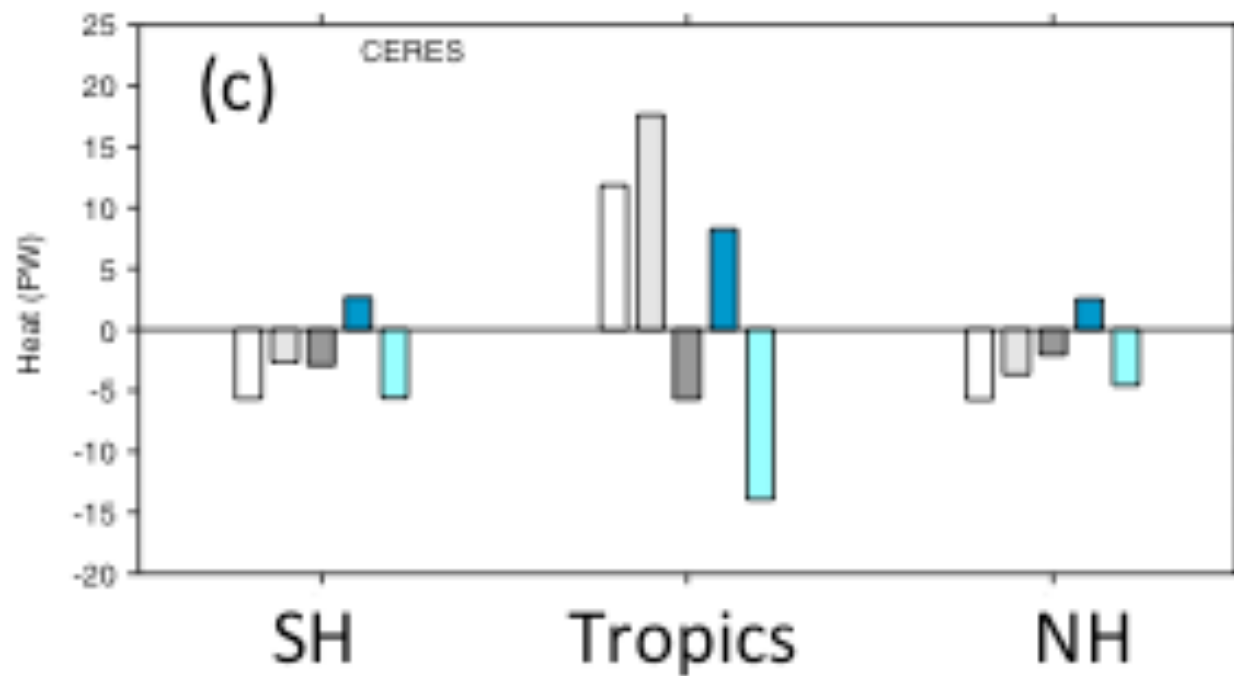
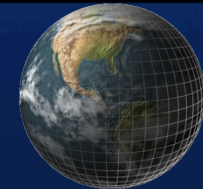
Lat of max
transport

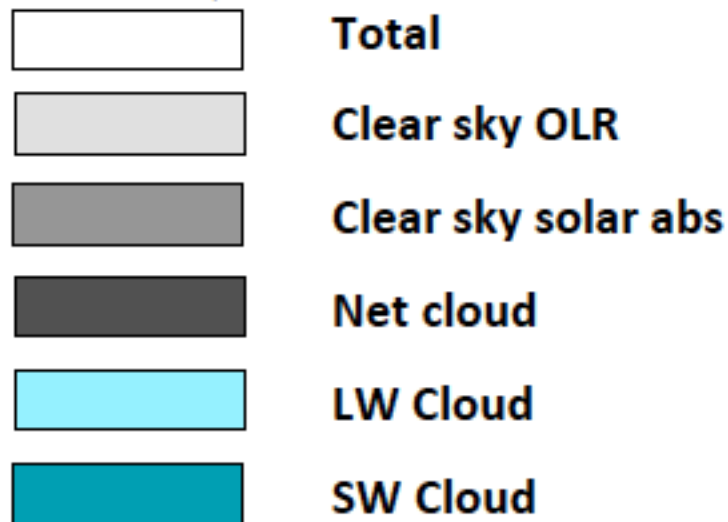
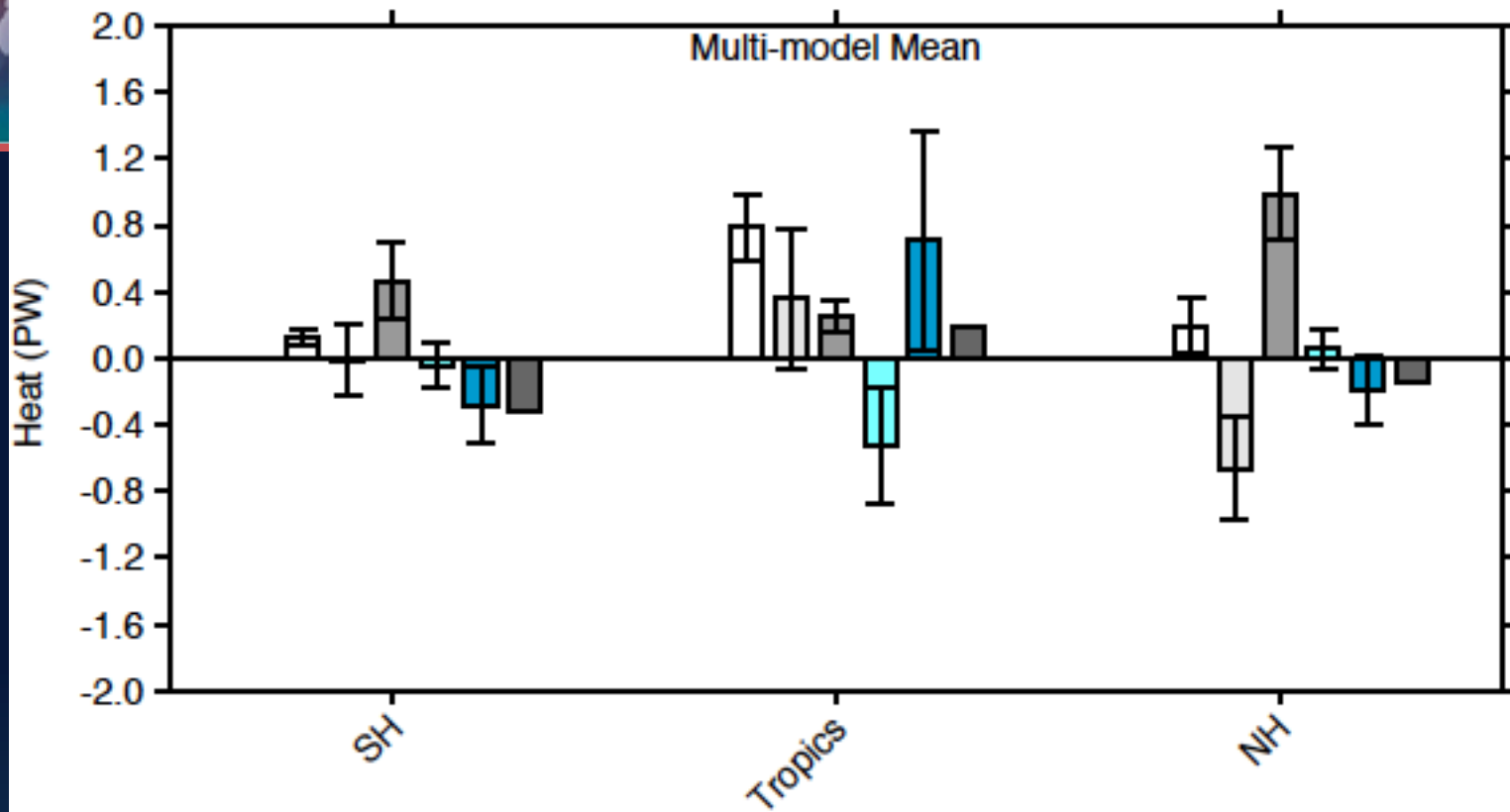
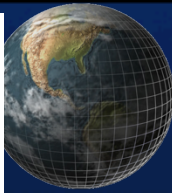
Stone, 1978 argues that the hemispheric albedo and solar geometry set the absorbed solar distribution which in turn primarily governs the transport of heat

Certain key characteristics of the net energy balance dictate the properties of the heat transport. In this framework, it is possible to trace the influence of processes relevant to this net flux distribution to the heat transport

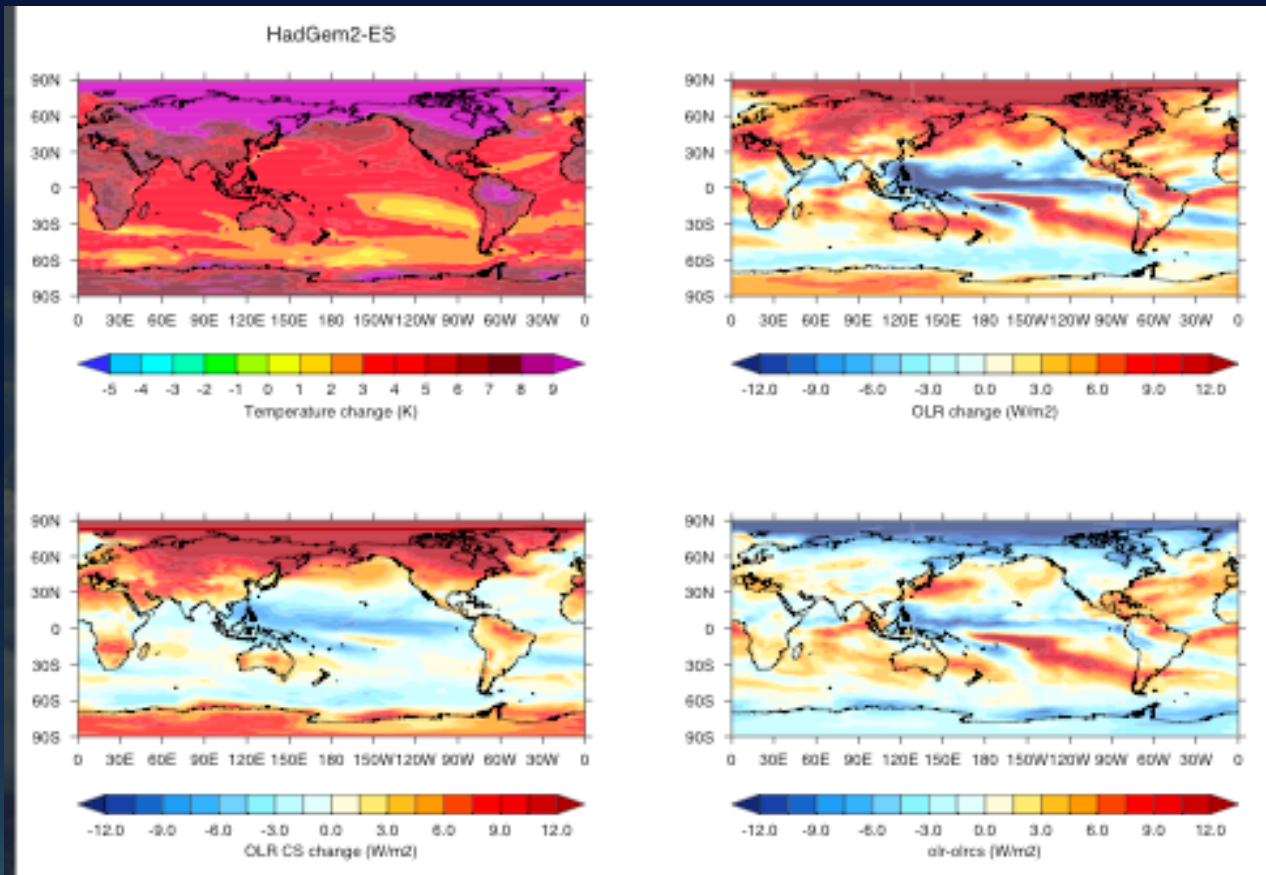


This accumulated deficit sets the level of the max value of the hemispheric transport





The regions of enhanced heat uptake and reduced emission (super-greenhouse regions) are determined by upper tropospheric water vapor & clouds with the change largely ($\sim 70\%$) from emission at $\lambda > 15\mu\text{m}$ (the far IR, Stephens and Kahn, 2014, in prep)



An example of one model from CMIP5 1% transient experiment
- differences of year 130-140 minus year 0-10 averages